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The Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP)

Citation for published version:

Keller, DP, Lenton, A, Scott, V, Vaughan, NE, Bauer, N, Ji, D, Jones, CD, Kravitz, B, Muri, H & Zickfeld, K 2018, 'The Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP): rationale and experimental protocol for CMIP6 ', *Geoscientific Model Development*. <https://doi.org/10.5194/gmd-2017-168>

Digital Object Identifier (DOI):

[10.5194/gmd-2017-168](https://doi.org/10.5194/gmd-2017-168)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Geoscientific Model Development

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The Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP): Rationale and experimental design

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47 **Abstract**

48
49 The recent IPCC reports state that continued anthropogenic greenhouse gas
50 emissions are changing the climate threatening “severe, pervasive and
51 irreversible” impacts. Slow progress in emissions reduction to mitigate climate
52 change is resulting in increased attention on what is called *Geoengineering*,
53 *Climate Engineering*, or *Climate Intervention* – deliberate interventions to counter
54 climate change that seek to either modify the Earth’s radiation budget or remove
55 greenhouse gases such as CO₂ from the atmosphere. When focused on CO₂, the
56 latter of these categories is called Carbon Dioxide Removal (CDR). The majority
57 of future emission scenarios that stay well below 2°C, and nearly all emission
58 scenarios that do not exceed 1.5°C warming by the year 2100, require some form
59 of CDR. At present, there is little consensus on the impacts and efficacy of the
60 different types of proposed CDR. To address this need the Carbon Dioxide
61 Removal Model Intercomparison Project (or CDR-MIP) was initiated. This project
62 brings together models of the Earth system in a common framework to explore
63 the potential, impacts, and challenges of CDR. Here, we describe the first set of
64 CDR-MIP experiments that are designed to address questions concerning CDR-
65 induced climate “reversibility”, the response of the Earth system to direct
66 atmospheric CO₂ removal (direct air capture and storage), and the CDR potential
67 and impacts of afforestation/reforestation, as well as ocean alkalization.

68

69



70 1. Introduction

71

72 The Earth system is sensitive to the concentration of atmospheric
73 greenhouse gases (GHG) because they have a direct impact on the planetary
74 energy balance (Hansen, 2005), and in many cases also on biogeochemical
75 cycling (IPCC, 2013). The concentration of one particularly important GHG,
76 carbon dioxide (CO₂), has increased from approximately 277 ppm in the year
77 1750 to over 400 ppm today as a result of anthropogenic activities (Dlugokencky
78 and Tans, 2016; Le Quéré et al., 2015). This CO₂ increase, along with other GHG
79 increases and anthropogenic activities (e.g. land use change), has perturbed the
80 Earth's energy balance leading to an observed global mean surface air
81 temperature increase of around 0.8 °C above preindustrial levels in the year
82 2015 [updated from Morice et al. (2012)]. Biogeochemistry on land and in the
83 ocean has also been affected by the increase in CO₂, with a well-observed
84 decrease in ocean pH being one of the most notable results (Gruber, 2011;
85 Hofmann and Schellnhuber, 2010). Many of the changes caused by this rapid
86 temperature increase and perturbation of the carbon cycle have been
87 detrimental for natural and human systems (IPCC, 2014a).

88 While recent trends suggest that the atmospheric CO₂ concentration is
89 likely to continue to increase (Peters et al., 2013; Riahi et al., 2017), the Paris
90 Agreement of the 21st session of the Conference of Parties (COP21) on climate
91 change (UNFCCC, 2016) has set the goal of limiting warming to well below 2°C
92 (ideally no more than 1.5°C) relative to the global mean preindustrial
93 temperature. Even if significant efforts are made to reduce CO₂ emissions, it will
94 likely take decades before net emissions approach zero (Bauer et al., 2017; Riahi
95 et al., 2017; Rogelj et al., 2015a), a level that is likely required to reach and
96 maintain such temperature targets (Rogelj et al., 2015b). Changes in the climate
97 will therefore continue for some time, with future warming strongly dependent
98 on cumulative CO₂ emissions (Allen et al., 2009; IPCC, 2013; Matthews et al.,
99 2009), and there is the possibility that “severe, pervasive and irreversible”
100 impacts will occur if too much CO₂ is emitted (IPCC, 2013, 2014a). The lack of
101 agreement on how to sufficiently reduce CO₂ emissions in a timely manner, and
102 the magnitude of the task required to transition to a low carbon world has led to



103 increased attention on what is called *Geoengineering*, *Climate Engineering*, or
104 *Climate Intervention*. These terms are all used to define actions that deliberately
105 manipulate the climate system in an attempt to ameliorate or reduce the impact
106 of climate change by either modifying the Earth's radiation budget (Solar
107 Radiation Management, or SRM), or by removing the primary greenhouse gas,
108 CO₂, from the atmosphere (Carbon Dioxide Removal, or CDR) (National Research
109 Council, 2015). In particular, there is an increasing focus and study on the
110 potential of carbon dioxide removal (CDR) methods to offset emissions and
111 eventually to enable "net negative emissions", whereby more CO₂ is removed via
112 CDR than is emitted by anthropogenic activities, to complement emissions
113 reduction efforts. CDR has also been proposed as a means of "reversing" climate
114 change if too much CO₂ is emitted, i.e., CDR may be able to reduce atmospheric
115 CO₂ to return radiative forcing to some target level.

116 Almost all future scenarios state that some form of CDR may be needed to
117 prevent the mean global surface temperature from exceeding 1.5°C (Rogelj et al.,
118 2015a). The majority of scenarios that limit warming to ≤2°C also include CDR
119 (Bauer et al., 2017; Fuss et al., 2014; Kriegler et al., 2016). Most of these limited
120 warming scenarios feature overshoots in radiative forcing around mid-century,
121 which is closely related to the amount of cumulative CDR up until the year 2100
122 (Kriegler et al., 2013). Despite the prevalence of CDR in these scenarios, and its
123 increasing utilization in political and economic discussions, many of the methods
124 by which this would be achieved at this point rely on immature technologies
125 (National Research Council, 2015; Schäfer et al., 2015). Large scale CDR methods
126 have not been a commercial product, and hence questions remain about their
127 feasibility, realizable potential and risks (Smith et al., 2015; Vaughan and Gough,
128 2016).

129 Overall, knowledge about the potential climatic, biogeochemical,
130 biogeophysical, and other impacts in response to CDR is still quite limited, and
131 large uncertainties remain, making it difficult to comprehensively evaluate the
132 potential and risks of any particular CDR method and make comparisons
133 between methods. This information is urgently needed to assess:

134



- 135 i. The degree to which CDR could help mitigate or perhaps reverse climate
136 change;
- 137 ii. The potential effectiveness and risks/benefits of different CDR proposals;
138 and
- 139 iii. To inform how climate and carbon cycle responses to CDR could be
140 included in calculating and accounted for the contribution of CDR in
141 mitigation scenarios.

142

143 To date, modelling studies of CDR focusing on the carbon cycle and
144 climatic responses have been undertaken with only a few Earth system models
145 (Arora and Boer, 2014; Boucher et al., 2012; Cao and Caldeira, 2010; Gasser et al.,
146 2015; Jones et al., 2016a; Keller et al., 2014; MacDougall, 2013; Mathesius et al.,
147 2015; Tokarska and Zickfeld, 2015; Zickfeld et al., 2016). However, as these
148 studies all use different experimental designs, their results are not directly
149 comparable, consequently building a consensus on responses is challenging. A
150 model intercomparison study with Earth System Models of Intermediate
151 Complexity (EMICS) that addresses climate reversibility, among other things, has
152 recently been published (Zickfeld et al., 2013), but the focus was on the very
153 distant future rather than this century. Moreover, in many of these studies,
154 atmospheric CO₂ concentrations were prescribed rather than being driven by
155 CO₂ emissions and thus, the projected changes were independent of the strength
156 of feedbacks associated with the carbon cycle.

157 Given that Earth system models are one of the few tools available for
158 making quantifications at these scales, as well as for making projections into the
159 future, CDR assessments must include emissions-driven modeling studies to
160 capture the carbon-cycle feedbacks. However, such an assessment cannot be
161 done with one or two models alone, since this will not address uncertainties due
162 to model structure and internal variability. Below we describe the scientific foci
163 and several experiments (Table 1) that comprise the initial phase of the Carbon
164 Dioxide Removal Model Intercomparison Project (CDR-MIP).

165

166 1.2 CDR-MIP Scientific Foci

167



168 There are four principal science motivations behind CDR-MIP. First and
169 foremost, CDR-MIP will provide information that can be used to help assess the
170 potential and risks of using CDR to address climate change. A thorough
171 assessment will need to look at both the impacts of CDR upon the Earth system
172 and human society. CDR-MIP will focus primarily on Earth system impacts, with
173 the anticipation that this information will also be useful for understanding
174 potential impacts upon society. These scientific outcomes will lead to more
175 informed decisions about the role CDR may play in climate change mitigation
176 (defined here as a human intervention to reduce the sources or enhance the
177 sinks of greenhouse gases). Second, CDR-MIP experiments will provide an
178 opportunity to better understand how the Earth system responds to
179 perturbations, which is relevant to many of the Grand Science Challenges posed
180 by the World Climate Research Program (WCRP; [https://www.wcrp-](https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview)
181 [climate.org/grand-challenges/grand-challenges-overview](https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview)). CDR-MIP
182 experiments provide a unique opportunity because the perturbations are often
183 opposite in sign to previous CMIP perturbation experiments (CO₂ is removed
184 instead of added). Thirdly, CDR-MIP results may also be able to provide
185 information that helps to understand how model resolution and complexity
186 cause systematic model bias. In this instance, CDR-MIP experiments may be
187 especially useful for gaining a better understanding of the similarities and
188 differences between global carbon cycle models because we invite a diverse
189 group of models to participate in CDR-MIP. Finally, CDR-MIP results can help to
190 quantify uncertainties in future climate change scenarios, especially those that
191 include CDR. In this case CDR-MIP results may be useful for calibrating CDR
192 inclusion in Integrated Assessment Models (IAMs) during the scenario
193 development process.

194 The initial foci that are addressed by CDR-MIP include (but are not limited
195 to):

196
197 (i) Climate “reversibility”: assessing the efficacy of using CDR to return high
198 future atmospheric CO₂ concentrations to lower levels. This topic is highly
199 idealized, as the technical ability of CDR methods to remove such enormous
200 quantities of CO₂ on relatively short timescales (i.e., this century) is doubtful.



201 However, the results will provide information on the degree to which a changing
202 and changed climate could be returned to a previous state. This knowledge is
203 especially important since socio-economic scenarios that limit global warming to
204 well below 2° C often feature radiative forcing overshoots that must be
205 "reversed" using CDR. We also anticipate that knowledge of reversibility
206 potential will be useful during the development of societal strategies for climate
207 change adaptation. Specific questions on reversibility will address:

208

- 209 1) What components of the Earth's climate system exhibit "reversibility"
210 when CO₂ increases and then decreases? On what timescales do these
211 "reversals" occur? And if reversible, is this complete reversibility or
212 just on average (are there spatial and temporal aspects)?
- 213 2) Which, if any, changes are irreversible?
- 214 3) What role does hysteresis play in these responses?

215

216 (ii) The potential efficacy, feedbacks, and side effects of specific CDR methods.
217 Efficacy is defined here as CO₂ removed from the atmosphere, over a specific
218 time horizon, as a result of a specific unit of CDR action. This topic will help to
219 better constrain the carbon sequestration potential and risks and/or benefits of
220 selected methods. Together, a rigorous analysis of the nature, sign, and
221 timescales of these CDR-related topics will provide important information for the
222 inclusion of CDR in climate mitigation scenarios, and in resulting mitigation and
223 adaptation policy strategies. Moreover, such studies will be a good test for the
224 models, and could be used to improve their performance and realism. Specific
225 questions on individual CDR methods will address:

226

- 227 1) How much CO₂ would have to be removed to return to a specified
228 concentration level e.g. present day or pre-industrial?
- 229 2) What are the short-term carbon cycle feedbacks (e.g. rebound)
230 associated with the method?
- 231 3) What are the short- and longer-term physical/chemical/biological
232 impacts and feedbacks, and potential side effects of the method?



233 4) For methods that enhance natural carbon uptake, e.g., afforestation
 234 or ocean alkalization, where is the carbon stored (land and
 235 ocean) and for how long (i.e. issues of permanence)?
 236

237 **1.3 Structure of this document**

238
 239 Our motivation for preparing this document is to lay out in detail the
 240 CDR-MIP experimental protocol, which we request all modelling groups to follow
 241 as closely as possible. Firstly, in Section 2, we review the scientific background
 242 and motivation for CDR in more detail than covered in this introduction. Section
 243 3 describes some requirements and recommendations for participating in CDR-
 244 MIP and describes links to other CMIP6 activities. Section 4 describes each CDR-
 245 MIP simulation in detail. Section 5 describes the model output and data policy.
 246 Section 6 presents an outlook of potential future CDR-MIP activities and a
 247 conclusion.
 248

249 **2. Background and motivation**

250
 251 At present, there are two main proposed CDR approaches, which we
 252 briefly introduce here. The first category encompasses methods that are
 253 primarily designed to enhance the Earth's natural carbon sequestration
 254 mechanisms. Enhancing natural oceanic and terrestrial carbon sinks is suggested
 255 because these sinks have already *each* taken up over a quarter of the carbon
 256 emitted as a result of anthropogenic activities (Le Quéré et al., 2016) and have
 257 the capacity to store additional carbon, although this is subject to environmental
 258 limitations. Some prominent proposed sink enhancement methods include
 259 afforestation or reforestation, enhanced terrestrial weathering, biochar, land
 260 management to enhance soil carbon storage, ocean fertilization, ocean
 261 alkalization, and coastal management of blue carbon sinks.

262 The second general CDR category includes methods that rely primarily on
 263 technological means to directly remove carbon from the atmosphere, ocean, or
 264 land and isolate it from the climate system, e.g., storage in a geological reservoir
 265 (Scott et al., 2015). Methods that are primarily technological are suggested



266 because they may not be as limited by environmental constraints. Some
267 prominent proposed technological methods include direct CO₂ air capture with
268 storage and seawater carbon capture (and storage). One other proposed CDR
269 method, bioenergy with carbon capture and storage (BECCS), relies on both
270 natural processes and technology. BECCS is thus, constrained by some
271 environmental limitations, but because of its technical aspect may have a higher
272 CDR potential than if the same deployment area were used for sink-enhancing
273 CDR.

274 From an Earth system perspective, the potential and impacts of proposed
275 CDR methods have only been investigated in a few individual studies - see recent
276 climate intervention assessments for a broad overview of the state of CDR
277 research (National Research Council, 2015; Rickels et al., 2011; The Royal
278 Society, 2009; Vaughan and Lenton, 2011) and references therein. These studies
279 agree that CDR application at a large scale ($\geq 1\text{Gt CO}_2 \text{ yr}^{-1}$) would likely have a
280 substantial impact on the climate, biogeochemistry and the ecosystem services
281 that the Earth provides, i.e., the benefits humans obtain from ecosystems
282 (Millennium Ecosystem Assessment, 2005). Idealized Earth system model
283 simulations suggest that CDR does appear to be able to limit or even reverse
284 warming and changes in many other key climate variables (Boucher et al., 2012;
285 Tokarska and Zickfeld, 2015; Wu et al., 2014; Zickfeld et al., 2016). However,
286 less idealized studies, e.g., when some environmental limitations are accounted
287 for, suggest that many methods have only a limited individual mitigation
288 potential (Boysen et al., 2016, 2017; Keller et al., 2014; Sonntag et al., 2016).

289 Studies have also focused on the carbon cycle response to the deliberate
290 redistribution of carbon between dynamic carbon reservoirs or permanent
291 (geological) carbon removal. Understanding and accounting for the feedbacks
292 between these reservoirs in response to CDR is particularly important for
293 understanding the efficacy of any method (Keller et al., 2014). For example,
294 when CO₂ is removed from the atmosphere in simulations, the rate of oceanic
295 CO₂ uptake, which has historically increased in response to increasing emissions,
296 is reduced and might eventually reverse (i.e., net outgassing), because of a
297 reduction in the air-sea flux disequilibrium (Cao and Caldeira, 2010; Jones et al.,
298 2016a; Tokarska and Zickfeld, 2015; Vichi et al., 2013). Equally, the terrestrial



299 carbon sink also weakens in response to atmospheric CO₂ removal, and can also
300 become a source of CO₂ to the atmosphere (Cao and Caldeira, 2010; Jones et al.,
301 2016a; Tokarska and Zickfeld, 2015). This ‘rebound’ carbon flux response that
302 weakens or reverses carbon uptake by natural carbon sinks would oppose CDR
303 and needs to be accounted for if the goal is to limit or reduce atmospheric CO₂
304 concentrations to some specified level (IPCC, 2013).

305 In addition to the climatic and carbon cycle effects of CDR, most methods
306 appear to have side effects (Keller et al., 2014). The impacts of these side effects
307 tend to be method specific and may amplify or reduce the climate change
308 mitigation potential of the method. Some significant side effects are caused by
309 the spatial scale (e.g., millions of km²) at which many methods would have to be
310 deployed to have a significant impact upon CO₂ and global temperatures (Boysen
311 et al., 2016; Heck et al., 2016; Keller et al., 2014). For example, large-scale
312 afforestation could change regional albedo and so have a biogeophysical impact
313 on the Earth's energy budget and climate (Betts, 2000; Keller et al., 2014). Side
314 effects can also potentially alter the natural environment by disrupting
315 biogeochemical and hydrological cycles, ecosystems, and biodiversity (Keller et
316 al., 2014). For human societies, this means that CDR-related side effects could
317 potentially impact the ecosystem services provided by the land and ocean (e.g.,
318 food production), with the information so far suggesting that there could be both
319 positive and negative impacts on these services. Such effects could change
320 societal responses and strategies for adaptation if large-scale CDR were to be
321 deployed.

322 CDR deployment scenarios have focused on both preventing climate
323 change and reversing it. While there is some understanding of how the Earth
324 system may respond to CDR, as described above, another dynamic comes into
325 play if CDR were to be applied to “reverse” climate change. This is because if
326 CDR were deployed for this purpose, it would deliberately change the climate,
327 i.e., drive it in another direction, rather than just prevent it from changing by
328 limiting CO₂ emissions. Few studies have investigated how the Earth system may
329 respond if CDR is applied in this manner. The link between cumulative CO₂
330 emissions and global mean surface air temperature change has been extensively
331 studied (IPCC, 2013). Can this change simply be reversed by removing the CO₂



that has been emitted since the preindustrial era? Little is known about how reversible this relationship is, or whether it applies to other Earth system properties (e.g., net primary productivity, sea level, etc.). The few studies that have investigated CDR-induced climate reversibility have suggested that many Earth system properties are "reversible", but often with non-linear responses (Armour et al., 2011; Boucher et al., 2012; MacDougall, 2013; Tokarska and Zickfeld, 2015; Wang et al., 2014; Wu et al., 2014; Zickfeld et al., 2016). However, these analyses were generally limited to global annual mean values, and most models did not include potentially important components such as permafrost or terrestrial ice sheets. Thus, there are many unknowns and much uncertainty about whether it is possible to "reverse" climate change. Obtaining knowledge about climate "reversibility" is especially important as it could be used to direct or change societal responses and strategies for adaptation and mitigation.

2.1 Why a model intercomparison study on CDR?

Although ideas for controlling atmospheric CO₂ concentrations were proposed in the middle of the last century, it is only recently that CDR methods have received widespread attention as climate intervention strategies (National Research Council, 2015; Schäfer et al., 2015; The Royal Society, 2009; Vaughan and Lenton, 2011). While some proposed CDR methods do build upon substantial knowledge bases (e.g., soil and forest carbon, and ocean biogeochemistry), little research into large scale CDR has been conducted and limited research resources applied (National Research Council, 2015; Oschlies and Klepper, 2017). The small number of existing laboratory studies and small-scale field trials of CDR methods were not designed to evaluate climate or carbon cycle responses to CDR. At the same time it is difficult to conceive of how such an investigation could be carried out without scaling a method up to the point where it would essentially be "deployment". The few natural analogues that exist for some methods (e.g., weathering or reforestation) only provide limited insight into the effectiveness of deliberate large scale CDR. As such, beyond syntheses of resource requirements and availabilities (e.g., Smith, (2016), there is a lack of observational constraints that can be applied to the assessment of the



effectiveness of CDR methods. Lastly, many proposed CDR methods are pre-mature at this point and technology deployment strategies would be required to overcome this barrier (Schäfer et al., 2015), which means that they can only be studied in an idealized manner, i.e., through model simulations.

Understanding the response of the Earth system to CDR is urgently needed because CDR is increasingly being utilized to inform policy and economic discussions. Examples of this include scenarios that are being developed with GHG emission forcing that exceeds (or overshoots) what is required to limit global mean temperatures to 2° C or 1.5 °C, with the assumption that reversibility is possible with the future deployment of CDR. These scenarios are generated using Integrated Assessment Models, which compute the emissions of GHGs, short-lived climate forcers, and land-cover change associated with economic, technological and policy drivers to achieve climate targets. Most integrated assessment models represent BECCS as the only CDR option, with only a few also including afforestation (IPCC, 2014b). During scenario development and calibration the output from the IAMs is fed into climate models of reduced complexity, e.g., MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) (Meinshausen et al., 2011), to calculate the global mean temperature achieved through the scenario choices, e.g., those in the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017). These climate models are calibrated to Earth system models or through modelling intercomparison exercises like the Coupled Model Intercomparison Phase 5 (CMIP5), where much of the climate-carbon cycle information comes from the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP). However, since the carbon cycle feedbacks of large-scale negative CO₂ emissions have not been explicitly analyzed in projects like CMIP5, with the exception of Jones et al. (2016a), many assumptions have been made about the effects of CDR on the carbon cycle and climate. Knowledge of these short-term carbon cycle feedbacks is needed to better constrain the effectiveness of the CDR technologies assumed in the IAM generated scenarios.

This relates to the policy relevant question of whether in a regulatory framework, CO₂ removals from the atmosphere should be treated like emissions except for the opposite (negative) sign. The lack of this kind of analyses is a



398 knowledge gap in current climate modeling (Jones et al., 2016a) and relevant for
399 IAM models and political decisions. There is an urgent need to close this gap
400 since additional CDR options like the enhanced weathering of rocks on land or
401 direct air capture continue to be included in IAMs, e.g., Chen and Tavoni (2013).
402 Therefore, there is a need to better evaluate the climate-carbon cycle feedbacks
403 under CDR using Earth system models so that CDR is better constrained when it
404 is included in IAM generated scenarios.

405

406 **3. Requirements and recommendations for participation in CDR-MIP**

407

408 The CDR-MIP initiative is designed to bring together a suite of Earth
409 System Models, Earth System Models of Intermediate Complexity (EMICs), and
410 potentially even box models in a common framework. Models of differing
411 complexities are invited to participate because the questions posed above cannot
412 be answered with any single class of models. For example, ESMs are primarily
413 suited for investigations spanning only the next century because of the
414 computational expense, while EMICs and box models are well suited to
415 investigate the long-term questions surrounding CDR, but are often highly
416 parameterized and may not include important processes, e.g., cloud feedbacks.
417 The use of differing models will also provide insight into how model resolution
418 and complexity controls modeled short- and long-term climate and carbon cycle
419 responses to CDR.

420 All groups that are running models with an interactive carbon cycle are
421 encouraged to participate in CDR-MIP. We desire diversity and encourage groups
422 to use older models, with well-known characteristics, biases and established
423 responses (e.g. previous CMIP model versions), as well as state-of-the-art CMIP6
424 models. For longer model simulations, we would encourage modellers when
425 possible to include additional carbon reservoirs, such as ocean sediments or
426 permafrost, as these are not always implemented for short simulations. Models
427 that only include atmospheric and oceanic carbon reservoirs are welcome, and
428 will be able to participate in some experiments. All models wishing to participate
429 in CDR-MIP must provide clear documentation that details the model version,
430 components, and key run-time and initialization information (model time



stepping, spin-up state at initialization, etc.). Furthermore, all model output must be standardized to facilitate analyses and public distribution (see Sections 4 and 5).

3.1 Relations to other MIPs

We highly recommend that those who want to participate in CDR-MIP also conduct experiments from other MIPs. For models participating in CMIP6, and those running models that participated in CMIP5, the experiments, analyses, and assessments done for various MIPs can provide a valuable baseline and model sensitivities that can be used to better understand the response of these models when they conduct CDR-MIP simulations. In some cases these other MIP experiments also act as a control run for a CDR-MIP experiment or provide a pathway from which a CDR-MIP experiment branches (Sections 3.2 and 4, Tables 2-7). This is especially true for CMIP Diagnostic, Evaluation, and Characterization of Klima (DECK) and historical experiments as detailed in Eyring et al. (2016) for CMIP6, since they provide the basis for many experiments with almost all MIPs leveraging these in some way. Below we focus on links to ongoing MIPs that are endorsed by CMIP6, but note that earlier versions of many of these MIPs were part of CMIP5 and, thus, provide a similar synergy for any CMIP5 models participating in CDR-MIP.

The C4MIP will provide a baseline, standard protocols, and diagnostics for better understanding the relationship between the carbon cycle and the climate in CMIP6 (Jones et al., 2016b). Given the emphasis on carbon cycle perturbations in CDR-MIP, there is a strong synergy between C4MIP and CDR-MIP. Consequently, C4MIP will be invaluable for understanding model responses in CDR-MIP simulations. A key C4MIP experiment, the emissions-driven SSP5-8.5 scenario (a high CO₂ emission scenario with a radiative forcing of 8.5 Wm⁻² in year 2100) simulation, *esm-ssp585*, is also a control run and branching pathway for several CDR-MIP experiments. In addition, several CDR-MIP experiments may be valuable for understanding model responses during related C4MIP experiments. For example, one of the C4MIP experiments, *ssp534-over-bgc*, is a concentration driven "overshoot" scenario simulation that is run in a partially



464 coupled mode. The control run required for analyses of this simulation is a fully
465 coupled CO₂ concentration driven simulation of this scenario, *ssp534-over*, from
466 the Scenario Model Intercomparison Project (ScenarioMIP). A CDR-MIP
467 experiment, *C2_overshoot*, which is a fully coupled CO₂ emission driven version
468 of this scenario, will provide additional information that can be used to extend
469 the analyses to better understand climate-carbon cycle feedbacks.

470 The Land Use Model Intercomparison Project (LUMIP) is designed to
471 better understand the impacts of land-use and land-cover change on the climate
472 (Lawrence et al., 2016). The three main LUMIP foci overlap with some of the
473 CDR-MIP foci, especially in regards to land management as a CDR method (e.g.,
474 afforestation/reforestation). To facilitate land-use and land-cover change
475 investigations LUMIP provides standard protocols and diagnostics for the
476 terrestrial components of CMIP6 Earth system models. The inclusion of these
477 diagnostics will be important for all CDR-MIP experiments performed with
478 CMIP6 models. The CDR-MIP experiment on afforestation/reforestation, C3
479 (*esm-ssp585-ssp126Lu-ext*), is an extension of the LUMIP *esm-ssp585-ssp126Lu*
480 simulation. In this LUMIP experiment the C4MIP *esm-ssp585* scenario (a high CO₂
481 emission scenario) is simulated, but instead of using the standard SSP5-8.5 land
482 use forcing, the forcing from an afforestation/reforestation scenario (SSP1-2.6)
483 is used instead. In LUMIP this experiment is conducted from the year 2015 to
484 2100. CDR-MIP will extend the experiment well beyond this point (Section 4.3)
485 to investigate the long-term consequences of afforestation/reforestation in a
486 high-CO₂ world. Such an extended simulation will also be useful for answering
487 some of the LUMIP scientific questions.

488 ScenarioMIP is designed to provide multi-model climate projections for
489 several scenarios of future anthropogenic emissions and land use changes
490 (O'Neill et al., 2016). In addition to providing information on how models
491 respond to forcings, they act as baseline scenarios for many MIP experiments or
492 provide pathways from which MIP experiments branch. The ScenarioMIP SSP5-
493 3.4-OS experiments, *ssp534-over* and *ssp534-over-ext*, which prescribe
494 atmospheric CO₂ to follow an emission overshoot pathway that is followed by
495 aggressive mitigation to reduce emissions to zero by about 2070, with
496 substantial negative global emissions thereafter, are linked to CDR-MIP because



497 they act as control runs for our CO₂ emission driven version of this scenario.
498 Along with the partially coupled C4MIP version of this experiment, these
499 experiments will allow for qualitative comparative analyses to better understand
500 climate-carbon cycle feedbacks in an "overshoot" scenario with negative
501 emissions (CDR). If it is found that the carbon cycle effects of CDR are improperly
502 accounted for in the scenarios, then this information can be used to recalibrate
503 older CDR-including IAM scenarios and be used to better constrain CDR when it
504 is included in new scenarios.

505 The Ocean Model Intercomparison Project (OMIP), which primarily
506 investigates the ocean-related origins and consequences of systematic model
507 biases, will help to provide an understanding of ocean component functioning for
508 models participating in CMIP6 (Griffies et al., 2016). OMIP will also establish
509 standard protocols and output diagnostics for ocean model components. The
510 biogeochemical protocols and diagnostics of OMIP (Orr et al., 2016) are
511 particularly relevant for CMIP6 models participating in CDR-MIP. While the
512 inclusion of these diagnostics will be important for all CDR-MIP experiments,
513 these standards will be particularly important for facilitating the analysis of our
514 marine CDR experiment, *C4* (Section 4.4).

515

516 3.2 Prerequisite and recommended CMIP simulations

517

518 The following CMIP experiments are considered prerequisites for
519 specified CDR-MIP experiments (Tables 2- 7) and analyses:

520

521 • The CMIP prescribed atmospheric CO₂ pre-industrial control simulation,
522 *piControl*. This is required for all CDR-MIP experiments (many control
523 runs and experiment prerequisites branch from this) and is usually done
524 as part of the spin-up process.

525

526 • The CMIP6 pre-industrial control simulation with interactively simulated
527 atmospheric CO₂ (i.e., the CO₂ concentration is internally calculated, but
528 emissions are zero), *esm-piControl*. This is required for CDR-MIP
529 experiments *C2_pi-pulse*, *C2_overshoot*, *C3*, and *C4*.



- 530
- 531 • The CMIP 1 % per year increasing CO₂ simulation, *1pctCO₂*, that is
- 532 initialized from a pre-industrial CO₂ concentration with CO₂ then
- 533 increasing by 1% per year until the CO₂ concentration has quadrupled
- 534 (approximately 139 years). This is required for CDR-MIP experiment *C1*.
- 535
- 536 • The CMIP6 historical simulation, *historical*, where historical atmospheric
- 537 CO₂ forcing is prescribed along with land use, aerosols, and non-CO₂
- 538 greenhouse gases forcing. This is required for CDR-MIP experiment
- 539 *C2_yr2010-pulse*.
- 540
- 541 • The CMIP6 emissions driven historical simulation, *esm-hist*, where the
- 542 atmospheric CO₂ concentration is internally calculated in response to
- 543 historical anthropogenic CO₂ emissions forcing. Other forcing such as land
- 544 use, aerosols, and non-CO₂ greenhouse gases are prescribed. This is
- 545 required for CDR-MIP experiments *C2_overshoot*, *C3*, and *C4*.
- 546
- 547 • The LUMIP *esm-ssp585-ssp126Lu* simulation, which simulates
- 548 afforestation in a high CO₂ emission scenario, is the basis for CDR-MIP
- 549 experiment *esm-ssp585-ssp126Lu-ext*.
- 550
- 551 • The C4MIP *esm-ssp585* simulation, which is a high emission scenario and
- 552 serves as a control run and branching pathway for CDR-MIP *C4*
- 553 experiment.
- 554
- 555 We also highly recommend that groups run these additional C4MIP and
- 556 ScenarioMIP simulations:
- 557
- 558 • The ScenarioMIP *ssp534-over* and *ssp534-over-ext* simulations, which
- 559 prescribe the atmospheric CO₂ concentration to follow an emission
- 560 overshoot pathway that is followed by aggressive mitigation to reduce
- 561 emissions to zero by about 2070, with substantial negative global



emissions thereafter. These results can be qualitatively compared to CDR-MIP experiment *C2_overshoot*.

• The C4MIP *ssp534-over-bgc* and *ssp534-over-bgcExt* simulations, which are biogeochemically-coupled versions of the *ssp534-over* and *ssp534-over-ext* simulations, i.e., only the carbon cycle components (land and ocean) see the prescribed increase in the atmospheric CO₂ concentration; the model's radiation scheme sees a fixed preindustrial CO₂ concentration. These results can be qualitatively compared to CDR-MIP experiment *C2_overshoot*.

3.3 Simulation ensembles

We encourage participants whose models have internal variability to conduct multiple realizations, i.e. ensembles, for all experiments. While these are highly desirable, they are not mandatory, nor a prerequisite for participation in CDR-MIP. Therefore, the number of ensemble members is at the discretion of each modeling group. However, we strongly encourage groups to submit at least three ensemble members if possible.

3.4 Climate sensitivity calculation

Knowing the climate sensitivity of each model participating in CDR-MIP is important for interpreting the results. For modelling groups that have not already calculated their model's climate sensitivity, the required CMIP *1pctCO₂* can be used to calculate both the transient and equilibrium climate sensitivities. The transient climate sensitivity can be calculated as the difference in the global annual mean surface temperature between the start of the experiment and a 20-year period centered on the time of CO₂ doubling. The equilibrium response can be diagnosed following Gregory et al. (2004), Frölicher et al. (2013), or if possible (desirable) by running the model to an equilibrium state at 2×CO₂ or 4×CO₂.



594

595 **3.5 Model drift**

596

597 Model drift (Gupta et al., 2013; Séférian et al., 2015) is a concern for all
598 CDR-MIP experiments because if a model is not at an equilibrium state when the
599 experiment or prerequisite CMIP experiment begins, then the response to any
600 experimental perturbations could be confused by drift. Thus, before beginning
601 any of the experiments a model must be spun-up to eliminate long-term drift in
602 carbon reservoirs or fluxes. Groups participating in CMIP6 should follow the
603 C4MIP protocols described in Jones et al. (2016b), to ensure that drift is
604 acceptably small. If older model versions, e.g., CMIP5, are used for any
605 experiments, any known drift should be documented.

606

607 **4. Experimental Design and Protocols**

608

609 To facilitate multiple model needs, the experiments described below have
610 been designed to be relatively simple to implement. In most cases, they were also
611 designed to have high signal-to-noise ratios to better understand how the
612 simulated Earth system responds to significant CDR perturbations. While there
613 are many ways in which such experiments could be designed to address the
614 questions surrounding climate reversibility and each proposed CDR method, the
615 CDR-MIP like all MIPs, must be limited to a small number of practical
616 experiments. Therefore, after careful consideration, one experiment was chosen
617 specifically to address climate reversibility and several more were chosen to
618 investigate CDR by idealized direct air capture of CO₂ (DAC),
619 afforestation/reforestation, and ocean alkalization (Table 1). Experiments are
620 prioritized based on a tiered system, although, we encourage modelling groups
621 to complete the full suite of experiments. Unfortunately, limiting the number
622 experiments means that a number of potentially promising or widely utilized
623 CDR methods or combinations of methods must wait until a later time, i.e., a 2nd
624 phase, to be investigated in a multi-model context. In particular, the exclusion of
625 Biomass Energy with Carbon Capture and Storage (BECCS) is unfortunate, as this
626 is the primary CDR method in the Representative Concentration Pathways (RCP)



627 and Shared Socio-economic Pathways (SSP) scenarios used in CMIP5 and 6,
 628 respectively. However, there was no practical way to design a less idealized
 629 BECCS experiment as most state-of-the-art models are either incapable of
 630 simulating a biomass harvest with permanent removal or would require a
 631 substantial amount of reformulating to do so in a manner that allows comparable
 632 multi-model analyses.

633

634 **4.1. Climate and carbon cycle reversibility experiment (C1)**

635

636 If CO₂ emissions are not reduced quickly enough, and more warming
 637 occurs than is desirable or tolerable, then it is important to understand if CDR
 638 has the potential to "reverse" climate change. Here we propose an idealized Tier
 639 1 experiment that is designed to investigate CDR-induced climate "reversibility"
 640 (Fig. 1, Table 2). This experiment investigates the "reversibility" of the climate
 641 system by leveraging the prescribed 1% yr⁻¹ CO₂ concentration increase
 642 experiment that was done for prior CMIPs, and is a key run for CMIP6 (Eyring et
 643 al., 2016; Meehl et al., 2014). The CDR-MIP experiment starts from the 1% yr⁻¹
 644 CO₂ concentration increase experiment, *1pctCO2*, and then at the 4×CO₂
 645 concentration level prescribes a -1% yr⁻¹ removal of CO₂ from the atmosphere to
 646 pre-industrial levels (Fig. 1; this is also similar to experiments in Boucher et al.,
 647 (2012) and Zickfeld et al., (2016)). This approach is analogous to an unspecified
 648 CDR application or DAC, where CO₂ is removed to permanent storage to return
 649 atmospheric CO₂ to a prescribed level, i.e., a preindustrial concentration. To do
 650 this, CDR would have to counter emissions (unless they have ceased) as well as
 651 changes in atmospheric CO₂ due to the response of the ocean and terrestrial
 652 biosphere. We realize that the technical ability of CDR methods to remove such
 653 enormous quantities of CO₂ on such a relatively short timescale (i.e. in a few
 654 centuries) is doubtful. However, branching from the existing CMIP *1pctCO2*
 655 experiment provides a relatively straightforward opportunity, with a high signal-
 656 to-noise ratio, to explore the effect of large-scale removal of CO₂ from the
 657 atmosphere and issues involving reversibility (Fig. 2 shows exemplary *C1* results
 658 from two models). Moreover, since many modelling groups will have already
 659 conducted the first part of this experiment in preparation for other modelling



research, e.g., for CMIP, this should minimize the effort needed to perform the complete experiment.

4.1.1 Protocol for C1

Prerequisite simulations: Perform the CMIP *piControl* and the *1pctCO2* experiments. The *1pctCO2* experiment branches from the DECK *piControl* experiment, which should ideally represent a near-equilibrium state of the climate system under imposed year 1850 conditions. Note that *piControl* also serves as a control run for this CDR-MIP experiment. Starting from year 1850 conditions (*piControl* global mean atmospheric CO₂ should be 284.7 ppm) the *1pctCO2* simulation prescribes a CO₂ concentration increase at a rate of 1% yr⁻¹ (i.e., exponentially). The only externally imposed difference from the *piControl* experiment is the change in CO₂, i.e., all other forcing is kept at that of year 1850. A restart must be generated when atmospheric CO₂ concentrations are four times that of the *piControl* simulation (1138.8 ppm; this should be 140 years into the run). Groups that have already performed the *piControl* and *1pctCO2* simulations for CMIP5 or CMIP6 may provide a link to them if they are already on the Earth System Grid Federation (ESGF) that host CMIP data.

1pctCO2-cdr simulation: Use the 4×CO₂ restart from *1pctCO2* and prescribe a 1% yr⁻¹ removal of CO₂ from the atmosphere (start removal at the beginning of the 140th year: January 1st.) until the CO₂ concentration reaches 284.7 ppm (140 years of removal). As in *1pctCO2* the only externally imposed forcing should be the change in CO₂ (all other forcing is kept at that of year 1850). The CO₂ concentration should then be held at 284.7 ppm for as long as possible (a minimum of 60 years is required), with no change in other forcing. EMICs and box models are encouraged to extend runs for at least 1000 years (and up to 5000 years) at 284.7 ppm CO₂ to investigate long-term climate system and carbon cycle reversibility (see Fig. 2 b and d for examples of why it is important to understand the long-term response).

4.1.2 Model output frequency for experiment C1



693

694 Box models and EMICs without seasonality are expected to generate
695 annual global mean output for the duration of the experiment, while models with
696 seasonality are expected to generate higher spatial resolution data for most
697 simulations (Table 8). For the control run, *piControl*, we request that 100 years of
698 3-D model output be written monthly (this should be the last 100 years if
699 conducting a 500+ year run for CMIP6). For the *1pctCO2* and *1pctCO2-cdr*
700 simulations 3-D model output should be written monthly, i.e., as the atmospheric
701 CO₂ concentration is changing. We suggest that groups that have already
702 performed the *piControl* and *1pctCO2* simulations for CMIP5 or CMIP6 with an
703 even higher output resolution (e.g., daily) continue to use this resolution for the
704 *1pctCO2-cdr* simulation, as this will facilitate the analysis. For groups continuing
705 the simulations for up to 5000 years after CO₂ has returned to 284.7 ppm, at a
706 minimum, annual global mean values (non-gridded output) should be generated
707 after the initial minimum 60 years of higher resolution output. The data
708 formatting is described below in Section 5.

709

710 **4.2 Direct CO₂ air capture with permanent storage experiments (C2)**

711

712 The idea of directly removing excess CO₂ from the atmosphere (i.e.,
713 concentrations above pre-industrial levels) and permanently storing it in some
714 reservoir, such as a geological formation, is appealing because such an action
715 would theoretically address the main cause of climate change, anthropogenically
716 emitted CO₂ that remains in the atmosphere. Laboratory studies and small-scale
717 pilot plants have demonstrated that atmospheric CO₂ can be captured by several
718 different methods that are often collectively referred to as Direct Air Capture
719 (DAC) technology (Holmes and Keith, 2012; Lackner et al., 2012; Sanz-Pérez et
720 al., 2016). Technology has also been developed that can place captured carbon in
721 permanent reservoirs, i.e., Carbon Capture and Storage (CCS) methods (Matter et
722 al., 2016; Scott et al., 2013, 2015). DAC technology is currently prohibitively
723 expensive to deploy at large scales and may be technically difficult to scale up
724 (National Research Council, 2015), but does appear to be a potentially viable
725 CDR option. However, aside from the technical questions involved in developing



726 and deploying such technology, there remain questions about how the Earth
727 system would respond if CO₂ were removed from the atmosphere. As mentioned
728 in Section 2, the land and ocean components of the carbon cycle will respond to
729 any changes in atmospheric CO₂. These reservoirs, which are currently carbon
730 sinks, will oppose any effort to simply remove atmospheric CO₂ by either taking
731 up less carbon or by becoming carbon sources to the atmosphere if enough
732 carbon is removed (Jones et al., 2016a; Tokarska and Zickfeld, 2015; Vichi et al.,
733 2013). The carbon cycle is also strongly affected by the climate (Friedlingstein
734 and Prentice, 2010) and thus, its response to DAC will also depend on the past
735 and present state of the climate. These climate-carbon cycle feedbacks make it
736 difficult to determine exactly how much DAC would be needed to reach a specific
737 atmospheric CO₂ or temperature target. Only a few modelling studies have
738 investigated how the climate and carbon cycle respond to DAC (Cao and Caldeira,
739 2010; Jones et al., 2016a; Tokarska and Zickfeld, 2015) and there is much
740 uncertainty that needs to be overcome before quantitative estimates of DAC
741 efficacy can be made.

742 Here we propose a set of experiments that are designed to investigate and
743 quantify the response of the Earth system to idealized large-scale DAC. In all
744 experiments, atmospheric CO₂ is allowed to freely evolve to investigate carbon
745 cycle and climate feedbacks in response to DAC. The first two idealized
746 experiments described below use an instantaneous (*pulse*) CO₂ removal from the
747 atmosphere - approach for this investigation. Instantaneous CO₂ removal
748 perturbations were chosen since *pulsed* CO₂ addition experiments have already
749 been proven useful for diagnosing carbon cycle and climate feedbacks in
750 response to CO₂ perturbations. For example, previous positive CO₂ pulse
751 experiments have been used to calculate Global Warming Potential (GWP) and
752 Global Temperature change Potential (GTP) metrics (Joos et al., 2013). The
753 experiments described below build upon the previous positive CO₂ pulse
754 experiments, i.e., the PD100 and PI100 impulse experiments described in Joos et
755 al. (2013) where 100 Gt C is instantly added to preindustrial and near present
756 day simulated climates. However, our experiments also prescribe a negative CDR
757 pulse as opposed to just adding CO₂ to the atmosphere. Two experiments are
758 desirable because the Earth system response to CO₂ removal will be different



759 when starting from an equilibrium state versus starting from a perturbed state
760 (Zickfeld et al., 2016). One particular goal of these experiments is to estimate a
761 Global Cooling Potential (GCP) metric based on a CDR Impulse Response
762 Function (IRF_{CDR}). Such a metric will be useful for calculating how much CO₂ is
763 removed by DAC and how much DAC is needed to achieve a particular climate
764 target.

765 The third experiment, which focuses on "negative emissions", is based on
766 the Shared Socio-economic Pathway (SSP) 5-3.4-overshoot scenario and its long-
767 term extension (Kriegler et al., 2016; O'Neill et al., 2016). This scenario is of
768 interest to CDR-MIP because after an initially high level of emissions, which
769 follows the SSP5-8.5 unmitigated baseline scenario until 2040, CO₂ emissions are
770 rapidly reduced with net CO₂ emissions becoming negative after the year 2070
771 and continuing to be so until the year 2190 when they reach zero. In the original
772 SSP5-3.4-OS scenario, the negative emissions are achieved using BECCS.
773 However, as stated earlier there is currently no practical way to design a good
774 multi-model BECCS experiment. Therefore, in our experiments negative
775 emissions are achieved by simply removing CO₂ from the atmosphere and
776 assuming that it is permanently stored in a geological reservoir. While this may
777 violate the economic assumptions underlying the scenario, it still provides an
778 opportunity to explore the response of the climate and carbon cycle to
779 potentially achievable levels of negative emissions.

780 According to calculations done with a simple climate model, MAGICC
781 version 6.8.01 BETA (Meinshausen et al., 2011; O'Neill et al., 2016), the SSP5-3.4-
782 OS scenario considerably overshoots the 3.4 W m⁻² forcing level, with a peak
783 global mean temperature of about 2.4° C, before returning to 3.4 W m⁻² at the
784 end of the century. Eventually in the long-term extension of this scenario, the
785 forcing stabilizes just above 2 W m⁻², with a global mean temperature that should
786 equilibrate at about 1.25° C above pre-industrial temperatures. Thus, in addition
787 to allowing an investigation into the response of the climate and carbon cycle to
788 negative emissions, this scenario also provides the opportunity to investigate
789 issues of reversibility, albeit on a shorter timescale and with less of an
790 "overshoot" than in experiment C1.



One key motivation for choosing this particular scenario is that complimentary SSP5-3.4-OS scenario simulations are also being conducted for ScenarioMIP and C4MIP. The ScenarioMIP SSP5-3.4-OS experiments, a Tier 2 21st. Century simulation (*ssp534-over*) and the Tier 2 long-term extension simulation (*ssp534-over-ext*), are conducted with prescribed CO₂ forcing, which will provide a unique opportunity to compare how the climate and carbon cycle respond when CO₂ is prescribed versus when carbon cycle feedbacks are allowed to impact atmospheric CO₂ concentrations and simulated climate change. The Tier 2 C4MIP SSP5-3.4-OS experiments, *ssp534-over-bgc* and *ssp534-over-bgcExt*, are also conducted with prescribed CO₂ forcing. However, in these simulations only the carbon cycle components experience rising CO₂ (i.e., the model components are only partially coupled and CO₂ induced warming is not accounted for) so that carbon cycle and climate feedbacks can be better quantified. While not directly comparable, these differing MIP simulations of the same scenario will provide a set of results that can be used to address different aspects of what may happen in an "overshoot" scenario situation. The CDR-MIP experiment will also provide a direct test of an IAM assumption underlying parts of the SSP framework, namely that the SSP5-3.4-OS radiative forcing level can be achieved with the level of CDR assumed in the scenario.

810

811 **4.2.1 Instantaneous CO₂ removal / addition from an unperturbed climate** 812 **experimental protocol (*C2_pi-pulse*)**

813

This idealized Tier 1 experiment is designed to investigate how the Earth system responds to DAC when perturbed from an equilibrium state (Fig. 3, Table 3). The idea is to provide a baseline system response that can later be compared to the response of a perturbed system, i.e., experiment *C2_yr2010-pulse* (Section 4.2.3). By also performing another simulation where the same amount of CO₂ is added to the system, it will be possible to diagnose if the system responds in an inverse manner when the CO₂ pulse is positive. Many modelling groups will have already conducted the prerequisite simulation for this experiment in preparation for other modelling research, e.g., during model spin-up or for CMIP, which



823 should minimize the effort needed to perform the complete experiment. The
824 protocol is as follows:
825

826 *Prerequisite simulation* - Control simulation under preindustrial conditions with
827 freely evolving CO₂. All boundary conditions (solar forcing, land use, etc.) are
828 expected to remain constant. This is also the CMIP5 *esmControl* simulation
829 (Taylor et al., 2012) and the CMIP6 *esm-piControl* simulation (Eyring et al.,
830 2016). Note that this is exactly the same as PI100 run 4 in Joos et. al. (2013). For
831 groups that have not participated in CMIP5 or CMIP6, this run essentially
832 represents an equilibrium model state with no significant drift. We realize that it
833 is difficult for ESMs to reach a state with little drift and follow the guidelines
834 provided by Jones et al. (2016b), to define what is an acceptably small level of
835 drift in a properly spun-up model, e.g., land, ocean and atmosphere carbon stores
836 should each vary by less than 10 GtC per century (long-term average ≤ 0.1 Gt C
837 yr⁻¹). We leave it to individual groups to determine the length of the run required
838 to reach such a state and request only that 100 years of output at such an
839 equilibrium be made available.
840

841 *esm-pi-cdr-pulse* simulation - As in *esm-Control* or *esm-piControl*, but with 100 Gt
842 C instantaneously removed from the atmosphere in year 10. After the negative
843 pulse ESMs should continue the run for at least 100 years, while EMICs and box
844 models are encouraged to continue the run for at least 1000 years (and up to
845 5000 years if possible). Figure 4 shows example *esm-pi-cdr-pulse* model
846 responses.
847

848 *esm-pi-co2pulse* simulation - The same as *esm-pi-cdr-pulse*, but add a positive 100
849 Gt C pulse as in Joos et. al. (2013), instead of a negative one. Note that this would
850 be exactly the same as the PI100 run 5 in Joos et. al. (2013). This will be used to
851 investigate if, after positive and negative pulses, carbon cycle and climate
852 feedback responses, which are expected to be opposite in sign, differ in
853 magnitude and temporal scale. The results can also be compared to Joos et. al.
854 (2013).
855



856 **4.2.2 Model output frequency for experiment *C2_pi-pulse***

857

858 The model output frequency is listed in Table 8. If possible, 3-D model
 859 output should be written monthly for 10 years before the negative pulse and for
 860 100 years following the pulse. For groups that can perform longer simulations,
 861 e.g., thousands of years, at a minimum, annual global mean values (non-gridded
 862 output) should be generated. Box models are expected to generate annual global
 863 mean output for the duration of the simulation. Data for the control run, i.e., the
 864 equilibrium simulation *esm-piControl*, must also be available for analytical
 865 purposes. CMIP participants may provide a link to the *esm-Control* or *esm-*
 866 *piControl* data on the ESGF. The data formatting is described below in Section 5.

867

868 **4.2.3 Instantaneous CO₂ removal from a perturbed climate experimental** 869 **protocol (*C2_yr2010-pulse*)**

870

871 This Tier 2 experiment is designed to investigate how the Earth system
 872 responds when CO₂ is removed from an anthropogenically-altered climate not in
 873 equilibrium (Fig. 5, Table 4). Many modelling groups will have already conducted
 874 part of the first run of this experiment in preparation for other modelling
 875 research, e.g., CMIP, and may be able to use a "restart" file to initialize the first
 876 run, which should reduce the effort needed to perform the complete experiment.

877

878 *Prerequisite simulation* - Prescribed CO₂ run. Historical atmospheric CO₂ is
 879 prescribed until a concentration of 389ppm is reached (~year 2010; Fig. 5 top
 880 panel). An existing run or setup from CMIP5 or CMIP6 may also be used to reach
 881 a CO₂ concentration of 389ppm, e.g., the CMIP6 *historical* experiment. During this
 882 run, compatible emissions should be frequently diagnosed (at least annually).

883

884 *yr2010co2* simulation - Atmospheric CO₂ should be held constant at 389 ppm
 885 with other forcing, like land use and aerosol emissions, also held constant (Fig. 5
 886 top panel). ESMs should continue the run at 389ppm for at least 105 years, while
 887 EMICs and box models are encouraged to continue the run for as long as needed
 888 for the subsequent simulations (e.g., 1000+ years). During this run, compatible



889 emissions should be frequently diagnosed (at least annually). Note that when
890 combined with the prerequisite simulation described above this is exactly the
891 same as the PD100 run 1 in Joos et. al. (2013).
892
893 *esm-hist-yr2010co2-control* simulation - Diagnosed emissions control run. The
894 model is initialized from the pre-industrial period (i.e., using a restart from
895 either *piControl* or *esm-piControl*) with the emissions diagnosed in the *historical*
896 and *yr2010co2* simulations, i.e., year 1850 to approximately year 2115 for ESMs
897 and longer for EMICs and box models (up to 5000 years). Atmospheric CO₂ must
898 be allowed to freely evolve. The results should be quite close to those in the
899 *historical* and *yr2010co2* simulations. Note that this is exactly the same as the
900 PD100 run 2 in Joos et. al. (2013). As in Joos et al. (2013), if computational time
901 is an issue and if a group is sure that CO₂ remains at a nearly constant value with
902 the emissions diagnosed in *yr2010co2*, the *esm-hist-yr2010co2-control* simulation
903 may be skipped. This may only apply to ESMs and it is strongly recommended to
904 perform the *esm-hist-yr2010co2-control* simulation to avoid model drift.
905
906 *esm-yr2010co2-cdr-pulse* simulation - CO₂ removal simulation. Setup is initially
907 as in the *esm-hist-yr2010co2-control* simulation. However, a "negative" emissions
908 pulse of 100 GtC is subtracted instantaneously from the atmosphere 5 years after
909 the time at which CO₂ was held constant in the *esm-hist-yr2010co2-control*
910 simulation (this should be at the beginning of the year 2015), with the run
911 continuing thereafter for at least 100 years. EMICs and box models are
912 encouraged to extend the runs for at least 1000 years (and up to 5000 years). It
913 is crucial that the negative pulse be subtracted from a constant background
914 concentration of ~389 ppm. All forcing, including CO₂ emissions, must be exactly
915 as in the *esm-hist-yr2010co2-control* simulation so that the only difference
916 between these runs is that this one has had CO₂ instantaneously removed from
917 the atmosphere.
918
919 *esm-yr2010co2-noemit* - A zero CO₂ emissions control run. Setup is initially as in
920 the *esm-yr2010co2-cdr-pulse* simulation. However, at the time of the "negative"
921 emissions pulse in the *esm-yr2010co2-cdr-pulse* simulation, emissions are set to



922 zero with the run continuing thereafter for at least 100 years. EMICs and box
923 models are encouraged to extend the runs for at least 1000 years (and up to
924 5000 years). All other forcing must be exactly as in the *esm-yr2010co2-control*
925 simulation. This experiment will be used to isolate the Earth system response to
926 the negative emissions pulse in the *esm-yr2010co2-cdr-pulse* simulation, which
927 convolves the response to the negative emissions pulse with the lagged response
928 to the preceding positive CO₂ emissions (diagnosed with the zero emissions
929 simulation). The response to the negative emissions pulse will be calculated as
930 the difference between *esm-yr2010co2-cdr-pulse* and *esm-yr2010co2-noemit*
931 simulations.

932
933 *esm-yr2010co2-co2pulse* simulation - CO₂ addition simulation. Setup is initially as
934 in the *esm-yr2010co2-cdr-pulse* simulation. However, a "positive" emissions
935 pulse of 100 GtC is added instantaneously, with the run continuing thereafter for
936 a minimum of 100 years. EMICs and box models are encouraged to extend the
937 runs for at least 1000 years (and up to 5000 years). It is crucial that the positive
938 pulse be added to a constant background concentration of ~389 ppm. All
939 forcing, including CO₂ emissions, must be exactly as in the *esm-hist-yr2010co2-*
940 *control* simulation so that the only difference between these runs is that this one
941 has had CO₂ instantaneously added to the atmosphere. Note that this would be
942 exactly the same as PD100 run in Joos et. al. (2013). This will be used to
943 investigate if, after positive and negative pulses, carbon cycle and climate
944 feedback responses, which are expected to be opposite in sign, differ in
945 magnitude and temporal scale. The results can also be compared to Joos et. al.
946 (2013).

947 948 **4.2.4 Model output frequency for experiment C2_yr2010-pulse**

949
950 The model output frequency is listed in Table 8. For the *historical* and
951 *yr2010co2* simulations output is only needed to diagnose annual CO₂ emissions
952 and will not be archived on the ESGF. Gridded 3-D monthly mean output for the
953 *esm-hist-yr2010co2-control* (starting in the year 2010), *esm-yr2010co2-cdr-pulse*,
954 *esm-yr2010co2-noemit*, and *esm-yr2010co2-co2pulse* simulations should be



written for the initial 100 years of the simulation. Thereafter, for groups that can perform longer simulations (up to 5000 years), at a minimum annual global mean values (non-gridded output) should be generated. Box models or EMICs without a seasonal cycle are expected to generate annual global mean output for the *esm-hist-yr2010co2-control* (starting in the year 2010), *esm-yr2010co2-cdr-pulse*, *esm-yr2010co2-noemit*, and *esm-yr2010co2-co2pulse* simulations. CMIP participants are requested to provide a link to the *historical* simulation data on the ESGF. The data formatting is described below in Section 5.

963

964 **4.2.5 Emission driven SSP5-3.4-OS experimental protocol (*C2_overshoot*)**

965

This Tier 1 experiment explores CDR in an "overshoot" climate change scenario, the SSP5-3.4-OS scenario (Fig. 6, Table 5). To start, groups must perform the CMIP6 emission driven historical simulation, *esm-hist*. Then using this as a starting point, conduct an emissions-driven SSP5-3.4-OS scenario simulation, *esm-ssp534-over*, (starting on January 1, 2015) that includes the long-term extension to the year 2300, *esm-ssp535-over-ext*. All non-CO₂ forcing should be identical to that in the ScenarioMIP *ssp534-over* and *ssp534-over-ext* simulations. If computational resources are sufficient, we recommend that the *esm-ssp534-over-ext* simulation be continued for at least another 1000 years with year 2300 forcing. i.e., the forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years, to better understand processes that are slow to equilibrate, e.g., ocean carbon and heat exchange or permafrost dynamics.

We also highly recommend that groups conduct the ScenarioMIP *ssp534-over* and *ssp534-over-ext* and C4MIP *ssp534-over-bgc* and *ssp534-over-bgcExt* simulations as these runs will be invaluable for qualitative comparisons.

982

983 **4.2.6 Model output frequency for experiment *C2_overshoot***

984

The model output frequency is listed in Table 8. If possible, 3-D model output should be written monthly until the year 2300. We suggest that groups that have already performed the ScenarioMIP *ssp534-over* and *ssp534-over-ext*



and C4MIP *ssp534-over-bgc* and *ssp534-over-bgcExt* CMIP6 simulations with an even higher output resolution (e.g., daily) continue to use this resolution as this will facilitate analyses. For groups that can perform longer simulations, e.g., thousands of years, at a minimum annual global mean values (non-gridded output) should be generated for every year beyond 2300. Box models are expected to generate annual global mean output for the duration of the experiment. We recommend that CMIP participants provide a link to the *esm-hist* data on the ESGF. For analytical purposes, we also request that ScenarioMIP and C4MIP participants provide links to any completed *ssp534-over*, *ssp534-over-ext*, *ssp534-over-bgc* and *ssp534-over-bgcExt* simulation data on the ESGF. The data formatting is described below in Section 5.

4.3 Afforestation/reforestation experiment (C3)

Enhancing the terrestrial carbon sink by restoring or extending forest cover, i.e., reforestation and afforestation, has often been suggested as a potential CDR option (National Research Council, 2015; The Royal Society, 2009). Enhancing this sink is appealing because terrestrial ecosystems have cumulatively absorbed over a quarter of all fossil fuel emissions (Le Quéré et al., 2016) and could potentially sequester much more. This follows because while terrestrial ecosystems may be an overall global net carbon sink, anthropogenic land use change, such as deforestation or agricultural use, affects the exchange of carbon with the atmosphere and can locally cause CO₂ to be emitted instead of sequestered (Arneth et al., 2017). Thus, if some of these disturbed lands, which cover one third of the total land area, can be reforested then there is the potential for them to sequester carbon instead of emitting it (Pongratz et al., 2011). Planting and managing new forests (i.e., afforestation) could also potentially increase the strength of the terrestrial carbon sink by allowing more carbon to be sequestered in regions that are currently minor sinks (e.g., deserts). However, afforestation/reforestation as a CDR method to mitigate climate change will have limits and side effects. This is because land use change also affects the climate by altering other climatically important biogeochemical cycles (e.g., the nitrogen cycle) and terrestrial biophysical properties and processes,



1021 e.g., hydrological cycling, surface albedo and roughness length, biogenic aerosol
1022 production, etc. (Betts, 2000; Betts et al., 2007; Claussen et al., 2001; Pongratz et
1023 al., 2011; Unger, 2014). Furthermore, enhancing the terrestrial carbon sink will
1024 weaken the ocean carbon sink, which reduces the CDR potential of this method
1025 (Ridgwell et al., 2002). There is also the issue of permanence, i.e., how long will
1026 sequestered carbon remain in the terrestrial system if the climate keeps
1027 changing, land use (afforestation/reforestation) is reversed (deforestation), or a
1028 natural disturbance (pests, fire, etc.) occurs. These other limitations and side
1029 effects can reduce the afforestation/reforestation CDR potential and may
1030 potentially even enhance global warming rather than preventing it if not
1031 carefully planned (Betts, 2000; Keller et al., 2014; Sonntag et al., 2016).
1032 Moreover, there are socio-economic concerns and limitations about large-scale
1033 afforestation/reforestation, considering that land must also be available for
1034 agricultural use, i.e., food security.

1035 Most of the key questions concerning land use change are being
1036 addressed by LUMIP (Lawrence et al., 2016). These include investigations into
1037 the potential of afforestation/reforestation to mitigate climate change, for which
1038 they have designed four experiments (LUMIP Phase 2 experiments). However,
1039 three of these experiments are CO₂ concentration driven, and thus are unable to
1040 fully investigate the climate-carbon cycle feedbacks that are important for CDR-
1041 MIP. The LUMIP experiment where CO₂ emissions force the simulation, *esm-*
1042 *ssp585-ssp126Lu*, will allow for climate-carbon cycle feedbacks to be
1043 investigated. However, since this experiment ends in the year 2100 it is too short
1044 to answer some of the key CDR-MIP questions (Section 1.2). We have therefore
1045 decided to extend this LUMIP experiment within the CDR-MIP framework as a
1046 Tier 1 experiment (Table 6) to better investigate the longer-term CDR potential
1047 and risks of afforestation/reforestation.

1048 The LUMIP experiment, *esm-ssp585-ssp126Lu*, simulates
1049 afforestation/reforestation by combining a high SSP CO₂ emission scenario,
1050 SSP5-8.5, with a future land use change scenario from an alternative SSP
1051 scenario, SSP1-2.6, which has much greater afforestation/reforestation (Kriegler
1052 et al., 2016; Lawrence et al., 2016). By comparing this combination to the SSP5-
1053 8.5 baseline scenario, it will be possible to determine the CDR potential of this



particular afforestation/reforestation scenario in a high CO₂ world. This is similar to the approach of Sonntag et al. (2016) using RCP 8.5 emissions combined with prescribed RCP 4.5 land use.

4.3.1 C3 Afforestation/reforestation experimental protocol

Prerequisite simulations - Conduct the C4MIP emission-driven *esm-ssp585* simulation, which is a control run, and the LUMIP Phase 2 experiment *esm-ssp585-ssp126Lu* (Lawrence et al., 2016). Generate restart files in the year 2100.

esm-ssp585-ssp126Lu-ext simulation - Using the year 2100 restart from the *esm-ssp585-ssp126Lu* experiment, continue the run with the same LUMIP protocol (i.e., an emission driven SSP5-8.5 simulation with SSP1-2.6 land use instead of SSP5-8.5 land use) until the year 2300 using the SSP5-8.5 and SSP1-2.6 long-term extension data (O'Neill et al., 2016). If computational resources are sufficient, we recommend that the simulation be continued for at least another 1000 years with year 2300 forcing (i.e., forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years). This is to better understand processes that are slow to equilibrate, e.g., ocean carbon and heat exchange or permafrost dynamics, and the issue of permanence.

esm-ssp585ext simulation - The emission-driven *esmSSP5-8.5* simulation must be extended beyond the year 2100 to serve as a control run for the *esm-ssp585-ssp126Lu-ext* simulation. This will require using the ScenarioMIP *ssp585-ext* forcing, but driving the model with CO₂ emissions instead of prescribing the CO₂ concentration. If computational resources are sufficient, the simulation should be extended even further than in the official SSP scenario, which ends in year 2300, by keeping forcing constant after this time (i.e., forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years).

4.3.2 Model output frequency for experiment C3



1086 The model output frequency is listed in Table 8. If possible, 3-D model
1087 output should be written monthly until the year 2300. LUMIP participants may
1088 provide a link to the *esm-hist* and *esm-ssp585-ssp126Lu* data on the ESGF for the
1089 first portions of this run (until the year 2100). For groups that can perform
1090 longer simulations, e.g., thousands of years, at a minimum annual global mean
1091 values (non-gridded output) should be generated for every year beyond 2300.
1092 EMICs without a seasonal cycle are expected to generate annual global mean
1093 output for the duration of the experiment. The data formatting is described
1094 below in Section 5.

1095

1096 **4.4. Ocean alkalization experiment (C4)**

1097

1098 Enhancing the natural process of weathering, which is one of the key
1099 negative climate-carbon cycle feedbacks that removes CO₂ from the atmosphere
1100 on long time scales (Colbourn et al., 2015; Walker et al., 1981), has been
1101 proposed as a potential CDR method (National Research Council, 2015; The
1102 Royal Society, 2009). Enhanced weathering ideas have been proposed for both
1103 the terrestrial environment (Hartmann et al., 2013) and the ocean (Köhler et al.,
1104 2010; Schuiling and Krijgsman, 2006). We focus on the alkalization of the
1105 ocean given its capacity to take up vast quantities of carbon over relatively short
1106 time periods and its potential to reduce the rate and impacts of ocean
1107 acidification (Kroeker et al., 2013). The idea is to dissolve silicate or carbonate
1108 minerals in seawater to increase total alkalinity. Total alkalinity, which can
1109 chemically be defined as the excess of proton acceptors over proton donors with
1110 respect to a certain zero level of protons, is a measurable quantity that is related
1111 to the concentrations of species of the marine carbonate system (Wolf-Gladrow
1112 et al., 2007). It plays a key role determining the air-sea gas exchange of CO₂
1113 (Egleston et al., 2010). When total alkalinity is artificially increased in surface
1114 waters, it basically allows more CO₂ to dissolve in the seawater and be stored as
1115 ions such as bicarbonate or carbonate, i.e., the general methodology increases
1116 the carbon storage capacity of seawater.

1117 Theoretical work and idealized modelling studies have suggested that
1118 ocean alkalization may be an effective CDR method that is more limited by



1119 logistic constraints (e.g., mining, transport, and mineral processing) rather than
1120 natural ones, such as available ocean area, although chemical constraints and
1121 side effects do exist (González and Ilyina, 2016; Ilyina et al., 2013; Keller et al.,
1122 2014; Köhler et al., 2010, 2013). One general side effect of ocean alkalization, is
1123 that it increases the buffering capacity and pH of the seawater. While such a side
1124 effect could be beneficial or even an intended effect to counter ocean
1125 acidification (Feng et al., 2016), high levels of alkalinity may also be detrimental
1126 to some organisms (Cripps et al., 2013). Ocean alkalization likely also has
1127 method specific side effects. Many of these side effects are related to the
1128 composition of the alkalizing agent, e.g., olivine may contain nutrients or toxic
1129 heavy metals, which could affect marine organisms and ecosystems (Hauck et al.,
1130 2016; Köhler et al., 2013). Other side effects could be caused by the mining,
1131 processing, and transport of the alkalizing agent, which in some cases may offset
1132 the CO₂ sequestration potential of specific ocean alkalization methods (e.g.,
1133 through CO₂ release by fossil fuel use or during the calcination of CaCO₃)
1134 (Kheshgi, 1995; Renforth et al., 2013).

1135 Although previous modelling studies have suggested that ocean
1136 alkalization may be a viable CDR method, these studies are not comparable due
1137 to different experimental designs. Here we propose an idealized Tier 1
1138 experiment (Table 7) that is designed to investigate the response of the climate
1139 system and carbon cycle to ocean alkalization. The amount of any particular
1140 alkalizing agent that could be mined, processed, transported, and delivered to
1141 the ocean in a form that would easily dissolve and enhance alkalinity is poorly
1142 constrained (Köhler et al., 2013; Renforth et al., 2013). Therefore, the amount of
1143 alkalinity that is to be added in our experiment is set (based on exploratory
1144 simulations conducted with the CSIRO-Mk3L-COAL model) to have a cumulative
1145 effect on atmospheric CO₂ by the year 2100. This is comparable to the amount
1146 removed in the CDR-MIP instantaneous DAC simulations, i.e., an atmospheric
1147 reduction of ~100 Gt C; experiments *C2_pi-pulse* and *C2_yr2010-pulse*. The idea
1148 here is not to test the maximum potential of such a method, which would be
1149 difficult given the still relatively coarse resolution of many models and the way in
1150 which ocean carbonate chemistry is simulated, but rather to compare the
1151 response of models to a significant alkalinity perturbation. We have also



1152 included an additional "termination" simulation that can be used to investigate
1153 an abrupt stop in ocean alkalization deployment.

1154

1155 **4.4.1 C4 Ocean alkalization experimental protocol**

1156

1157 Prerequisite simulation - Conduct the C4MIP emission-driven *esm-ssp585*
1158 simulation as described by Jones et al., (2016b). This is the SSP5-8.5 high CO₂
1159 emission scenario, and it serves as the control run and branching point for the
1160 ocean alkalization experiment. A restart must be generated at the end of the
1161 year 2019.

1162

1163 *esm-ssp585-ocean-alk* simulation - Begin an 80 year run using the *esm-ssp585*
1164 year 2020 restart (starting on Jan. 1, 2020) and add 0.14 Pmol Total Alkalinity
1165 (TA) yr⁻¹ to the upper grid boxes of each model's ocean component, i.e., branch
1166 from the C4MIP *esm-ssp585* simulation in 2020 until 2100. The alkalinity
1167 additions should be limited to mostly ice free, year-round ship accessible waters,
1168 which for simplicity should set to be between 70°N and 60°S (note that this
1169 ignores the presence of seasonal sea-ice in some small regions). For many
1170 models, this will in practice result in an artificial TA flux at the air-sea interface
1171 with realized units that might, for example, be something like μmol TA s⁻¹ cm⁻².
1172 Adding 0.14 Pmol TA yr⁻¹ is equivalent to adding 5.19 Pg yr⁻¹ of an alkalizing
1173 agent like Ca(OH)₂ or 4.92 Pg yr⁻¹ of forsterite (Mg₂SiO₄), a form of olivine
1174 (assuming theoretical net instant dissolution reactions which for every mole of
1175 Ca(OH)₂ or Mg₂SiO₄ added sequesters 2 or 4 moles, respectively, of CO₂ (Ilyina et
1176 al., 2013; Köhler et al., 2013)). As not all models include marine iron or silicate
1177 cycles, the addition of these nutrients, which could occur if some form of olivine
1178 were used as the alkalizing agent, is not considered here. All other forcing is as in
1179 the *esm-ssp585* control simulation. If the ocean alkalization termination
1180 simulation (below) is to be conducted, generate a restart at the beginning of the
1181 year 2070.

1182

1183 Optional (Tier 3) *esm-ssp585-ocean-alk-stop* simulation - Use the year 2070
1184 restart from the *esm-ssp585-ocean-alk* simulation and start a simulation



(beginning on Jan. 1, 2070) with the SPP5-8.5 forcing, but without adding any additional alkalinity. Continue this run until the year 2100, or beyond, if conducting the *esm-ssp585-ocean-alk-ext* simulation (below).

Optional (Tier 2) ocean alkalization extension simulations:

esm-ssp585ext simulation - If groups desire to extend the ocean alkalization experiment beyond the year 2100, an optional simulation may be conducted to extend the control run using forcing data from the ScenarioMIP *ssp585ext* simulation, i.e., conduct a longer emission-driven control run, *esm-ssp585ext*. This extension is also a control run for those conducting the CDR-MIP C3 afforestation/reforestation simulation (Section 4.3). If computational resources are sufficient, the simulation should be extended even further than in the official SSP scenario, which ends in year 2300, by keeping the forcing constant after this time (i.e., forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years).

esm-ssp585-ocean-alk-ext simulation - Continue the ocean alkalization experiment described above (i.e., adding 0.14 Pmol Total Alkalinity (TA) yr⁻¹ to the upper grid boxes of each model's ocean component) beyond the year 2100 (up to 5000 years) using forcing from the *esm-ssp585-ext* simulation.

4.4.2 Model output frequency for experiment C4

The model output frequency is listed in Table 8. If possible, 3-D gridded model output should be written monthly for all simulations. Models without a seasonal cycle are expected to generate annual global mean output for the duration of the experiment.

5. Model output formatting, data availability, and data use policy

5.1 Gridded model output



1217 Models capable of generating gridded data must use a NetCDF format. The
1218 output (see Appendix A web link for the list of requested variables) follows the
1219 CMIP6 output requirements in frequency and structure. This allows groups to
1220 use CMOR software (Climate Model Rewriter Software, available at
1221 <http://cmor.llnl.gov/>) to generate the files that will be available for public
1222 download (Section 5). CMOR3 tables for CDR-MIP are available at [www.kiel-](http://www.kiel-earth-institute.de/files/media/downloads/CDRmon.json)
1223 [earth-institute.de/files/media/downloads/CDRmon.json](http://www.kiel-earth-institute.de/files/media/downloads/CDRmon.json) (table for monthly
1224 output) and www.kiel-earth-institute.de/files/media/downloads/CDRga.json
1225 (table for global annual mean output). The resolution of the data should be as
1226 close to native resolution as possible, but on a regular grid. Please note as
1227 different models have different formulations, only applicable outputs need be
1228 provided. However, groups are encouraged to generate additional output, i.e.,
1229 whatever their standard output variables are, and can also make this data
1230 available (preferably following the CMIP6 CMOR standardized naming
1231 structure).

1232

1233 5.2 Conversion factor Gt C to ppm

1234

1235 For experiments where carbon must be converted between GtC (or Pg)
1236 and ppm CO₂, please use a conversion factor of 2.12 GtC per ppm CO₂ to be
1237 consistent with Global Carbon Budget (Le Quere et al., 2015) conversion factors.

1238

1239 5.3 Box model output

1240

1241 For models that are incapable of producing gridded NetCDF data (i.e., box
1242 models), output is expected to be in an ASCII format (Appendix B). All ASCII files
1243 are expected to contain tabulated values (at a minimum global mean values),
1244 with at least two significant digits for each run. Models must be able to calculate
1245 key carbon cycle variables (Appendix C) to participate in CDR-MIP experiments
1246 C1 and C2. Please submit these files directly to the corresponding author who
1247 will make them available for registered users to download from the CDR-MIP
1248 website.

1249



1250 **5.4 Data availability and use policy**

1251

1252 The model output from the CDR-MIP experiments described in this paper
1253 will be publically available. All gridded model output will, to the extent possible,
1254 be distributed through the Earth System Grid Federation (ESGF). Box model
1255 output will be available via the CDR-MIP website ([http://www.kiel-earth-](http://www.kiel-earth-institute.de/cdr-mip-data.html)
1256 [institute.de/cdr-mip-data.html](http://www.kiel-earth-institute.de/cdr-mip-data.html)). The CDR-MIP policy for data use is that if you
1257 use output from a particular model, you should contact the modeling group and
1258 offer them the opportunity to contribute as authors. Modeling groups will
1259 possess detailed understanding of their models and the intricacies of performing
1260 the CDR-MIP experiments, so their perspectives will undoubtedly be useful. At
1261 minimum, if the offer of author contribution is not taken up, CDR-MIP and the
1262 model groups should be credited in acknowledgments with for example a
1263 statement like: "*We acknowledge the Carbon Dioxide Removal Model*
1264 *Intercomparison Project leaders and steering committee who are responsible for*
1265 *CDR-MIP and we thank the climate modelling groups (listed in Table XX of this*
1266 *paper) for producing and making their model output available.*"

1267 The natural and anthropogenic forcing data that are required for some
1268 simulations are described in several papers in the Geoscientific Model
1269 Development CMIP6 special issue. These data will be available on the ESGF.
1270 Links to all forcing data can also be found on the CMIP6 Panel website
1271 (<https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6>). CMIP6 and CMIP5
1272 data should be acknowledged in the standard way.

1273

1274 **6. CDR-MIP outlook and conclusion**

1275

1276 It is anticipated that this will be the first stage of an ongoing project
1277 exploring CDR. CDR-MIP welcomes input on the development of other (future)
1278 experiments and scenarios. Potential future experiments could include Biomass
1279 Energy with Carbon Capture and Storage (BECCS) or ocean fertilization. Future
1280 experiments could also include the removal of non-CO₂ greenhouse gases, e.g.,
1281 methane, as these in many cases have a much higher global warming potential
1282 (de_Richter et al., 2017; Ming et al., 2016). We also envision that it will be



1283 necessary to investigate the simultaneous deployment of several CDR or other
1284 greenhouse gas removal methods since early studies suggest that there is likely
1285 not an individually capable method (Keller et al., 2014). It is also anticipated that
1286 scenarios will be developed that might combine Solar Radiation Management
1287 (SRM) and CDR in the future, such as a joint GeoMIP (Geoengineering Model
1288 Intercomparison Project) CDR-MIP experiment.

1289 In addition to reductions in anthropogenic CO₂ emissions, it is very likely
1290 that CDR will be needed to achieve the climate change mitigation goals laid out in
1291 the Paris Agreement. The potential and risks of large scale CDR are poorly
1292 quantified, raising important questions about the extent to which large scale CDR
1293 can be depended upon to meet Paris Agreement goals. This project, CDR-MIP, is
1294 designed to help us better understand how the Earth system might respond to
1295 CDR. Over the past two years the CDR-MIP team has developed a set of numerical
1296 experiments to be performed with Earth system models of varying complexity.
1297 The aim of these experiments is to provide coordinated simulations and analyses
1298 that addresses several key CDR uncertainties including:

- 1299
- 1300 • The degree to which CDR could help mitigate climate change or even
1301 reverse it.
 - 1302
 - 1303 • The potential effectiveness and risks/benefits of different CDR proposals
1304 with a focus on direct CO₂ air capture, afforestation/reforestation, and
1305 ocean alkalization.
 - 1306
 - 1307 • To inform how CDR might be appropriately accounted for within an Earth
1308 system framework and during scenario development.
 - 1309

1310 We anticipate that there will be numerous forthcoming studies that utilize
1311 CDR-MIP data. The model output from the CDR-MIP experiments will be
1312 publically available and we welcome and encourage interested parties to
1313 download this data and utilize it to further investigate CDR.

1314
1315



1316 **7. Code and/or data availability**

1317

1318 As described in Section 5.4, the output from models participating in CDR-
1319 MIP will be made publically available. This will include data used in exemplary
1320 Figs. 2 and 4. All gridded model output will be distributed through the Earth
1321 System Grid Federation (ESGF). Box model output will be available via the CDR-
1322 MIP website (<http://www.kiel-earth-institute.de/cdr-mip-data.html>). The code
1323 from the models used to generate the exemplary figures in this document (Figs. 2
1324 and 4, Appendix D) will be made available here via a web link when this
1325 manuscript is accepted for publication. To obtain code from modelling groups
1326 who are participating in CDR-MIP please contact the modelling group using the
1327 contact information that accompanies their data.

1328 The natural and anthropogenic forcing data that are required for some
1329 simulations are described in several papers in the Geoscientific Model
1330 Development CMIP6 special issue. These data will be available on the ESGF.
1331 Links to all forcing data can also be found on the CMIP6 Panel website
1332 (<https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6>).

1333

1334 *Acknowledgements.* D. P. Keller and N. Bauer acknowledge funding received from
1335 the German Research Foundation's Priority Program 1689 "Climate Engineering"
1336 (project CDR-MIA; KE 2149/2-1). K. Zickfeld acknowledges support from the
1337 Natural Sciences and Engineering Research Council of Canada (NSERC)
1338 Discovery grant program. The Pacific Northwest National Laboratory is
1339 operated for the U.S. Department of Energy by Battelle Memorial Institute under
1340 contract DE-AC05-76RL01830. D. Ji acknowledges support from the National
1341 Basic Research Program of China under grant number 2015CB953600. CDJ was
1342 supported by the Joint UK BEIS/ Defra Met Office Hadley Centre Climate
1343 Programme (GA01101) and by the European Union's Horizon 2020 research
1344 and innovation programme under grant agreement No 641816 (CRESCENDO).
1345 H. Muri was supported by Norwegian Research Council grant 261862/E10.

1346

1347

1348



1349 **Appendix A. Requested model output variables**

1350

1351 A spreadsheet of the requested model output variables and their format can be
 1352 found at: [www.kiel-earth-institute.de/files/media/downloads/CDR-](http://www.kiel-earth-institute.de/files/media/downloads/CDR-MIP_model_output_requirements.pdf)
 1353 [MIP_model_output_requirements.pdf](http://www.kiel-earth-institute.de/files/media/downloads/CDR-MIP_model_output_requirements.pdf). Please note as different models have
 1354 different formulations, only applicable outputs need be provided. However,
 1355 groups are encouraged to generate additional output, i.e., whatever their
 1356 standard output variables are, and can also make this data available.

1357

1358 **Appendix B. Box model output formatting**

1359

1360 Box model ASCII formatting example:

1361

1362 File name format: RUNNAME_MODELNAME_Modelversion.dat

1363 C1_MYBOXMODEL_V1.0_.dat

1364 Headers and formats:

1365 *Example:*

- 1366 • Start each header comment line with a #
- 1367 • *Line 1:* Indicate run name, e.g., "# esm-pi-cdr-pulse "
- 1368 • *Line 2:* Provide contact address, e.g., "# B. Box, Uni of Box Models, CO2
 1369 Str., BoxCity 110110, BoxCountry"
- 1370 • *Line 3:* Provide a contact email address, e.g., "# bbox@unibox.bx"
- 1371 • *Line 4:* Indicate model name, version, e.g., "# MyBoxModel Version 2.2"
- 1372 • *Line 5:* Concisely indicate main components, e.g., "# two ocean boxes
 1373 (upper and lower), terrestrial biosphere, and one atmospheric box"
- 1374 • *Line 6:* Indicate climate sensitivity of model, the abbreviation TCS may be
 1375 used for transient climate sensitivity and ECS for equilibrium climate
 1376 sensitivity, e.g., "# TCS=3.2 [deg C], ECS=8.1 [deg C]"
- 1377 • *Line 7:* Description of non-CO₂ forcing applied, e.g., "# Forcing: solar"
- 1378 • *Line 8:* Indicate the output frequency and averaging, e.g., "# Output: global
 1379 mean values"
- 1380 • *Line 9:* List tabulated output column headers with their units in brackets
 1381 (see table below), e.g., "# year tas[K]"



1382

1383 Complete Header Example:

1384 # *esm-pi-cdr-pulse*

1385 # B. Box, Uni. of Box Models, CO2 Str., BoxCity 110110, BoxCountry

1386 # bbox@unibox.bx

1387 # MyBoxModel Version 2.2

1388 # two ocean boxes (upper and lower), terrestrial biosphere, and one

1389 atmospheric box

1390 # TCS=3.2 deg C, ECS=8.1 deg C

1391 # Forcing: solar

1392 # Output: global mean values

1393 # year tas[K] co2[Gt C] nep[Gt C yr-1] fgco2[Gt C yr-1]

1394

1395 **Appendix C. Requested box model output variables**

1396

1397 Table of requested box model output (at a minimum as global mean values). To

1398 participate in CDR-MIP at a minimum the variables *tas*, *xco2*, and *fgco2* must be

1399 provided.

1400

Long name	Column Header Name*	Units	Comments
Relative year	year	year	
Near-surface Air Temperature	tas	K	
Atmospheric CO ₂	xco2	ppm	
Surface Downward CO ₂ flux into the ocean	fgco2	kg m ⁻²	This is the net air-to-ocean carbon flux (positive flux is into the ocean)
Total Atmospheric Mass of CO ₂	co2mass	kg	
Net Carbon Mass Flux out of Atmosphere due to Net Ecosystem Productivity on Land.	nep	kg m ⁻²	This is the net air-to-land carbon flux (positive flux is into the land)
Total ocean carbon	cOcean	Gt C	If the ocean contains multiple boxes this output can also be provided, e.g., as cOcean_up and cOcean_low for upper and lower ocean boxes



Total land carbon	cLand	Gt C	This is the sum of all C pools
Ocean Potential Temperature	thetao	K	Please report a mean value if there are multiple ocean boxes
Upper ocean pH	pH	1	Negative log of hydrogen ion concentration with the concentration expressed as mol H kg ⁻¹ .
Carbon Mass Flux out of Atmosphere due to Net Primary Production on Land	npp	kg m ⁻²	This is calculated as gross primary production – autotrophic respiration (gpp-ra)
Carbon Mass Flux into Atmosphere due to Heterotrophic Respiration on Land	rh	kg m ⁻²	
Ocean Net Primary Production by Phytoplankton	intpp	kg m ⁻²	

*Column header names follow the CMIP CMOR notation when possible

Appendix D. Model descriptions

The two models used to develop and test CDR-MIP experimental protocols and provide example results (Figs. 2 and 4) are described below.

The University of Victoria Earth System Climate model (UVic), version 2.9 consists of three dynamically coupled components: a three-dimensional general circulation model of the ocean that includes a dynamic-thermodynamic sea ice model, a terrestrial model, and a simple one-layer atmospheric energy-moisture balance model (Eby et al., 2013). All components have a common horizontal resolution of 3.6° longitude x 1.8° latitude. The oceanic component, which is in the configuration described by Keller et al. (2012), has 19 levels in the vertical with thicknesses ranging from 50 m near the surface to 500 m in the deep ocean. The terrestrial model of vegetation and carbon cycles (Meissner et al., 2003) is based on the Hadley Center model TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics). The atmospheric energy-moisture balance model interactively calculates heat and water fluxes to the



1420 ocean, land, and sea ice. Wind velocities, which are used to calculate the
1421 momentum transfer to the ocean and sea ice model, surface heat and water
1422 fluxes, and the advection of water vapor in the atmosphere, are determined by
1423 adding wind and wind stress anomalies. These are determined from surface
1424 pressure anomalies that are calculated from deviations in pre-industrial surface
1425 air temperature to prescribed NCAR/NCEP monthly climatological wind data
1426 (Weaver et al., 2001). The model has been extensively used in climate change
1427 studies and is also well validated under pre-industrial to present day conditions
1428 (Eby et al., 2009, 2013; Keller et al., 2012).

1429 The CSIRO-Mk3L-COAL Earth system model consists of a climate model,
1430 Mk3L (Phipps et al., 2011), coupled to a biogeochemical model of carbon,
1431 nitrogen and phosphorus cycles on land (CASA-CNP) in the Australian
1432 community land surface model, CABLE (Mao et al., 2011; Wang et al., 2010), and
1433 an ocean biogeochemical cycle model (Duteil et al., 2012; Matear and Hirst,
1434 2003). The atmospheric model has a horizontal resolution of 5.6° longitude by
1435 3.2° latitude, and 18 vertical layers. The land carbon model has the same
1436 horizontal resolution as the atmosphere. The ocean model has a resolution of
1437 2.8° longitude by 1.6° longitude, and 21 vertical levels. Mk3L simulates the
1438 historical climate well, as compared to the models used for earlier IPCC
1439 assessments (Phipps et al., 2011). Furthermore, the simulated response of the
1440 land carbon cycle to increasing atmospheric CO₂ and warming are consistent
1441 with those from the Coupled Model Intercomparison Project Phase 5 (CMIP5)
1442 (Zhang et al., 2014). The ocean biogeochemical model was also shown to
1443 realistically simulate the global ocean carbon cycle (Duteil et al., 2012; Matear
1444 and Lenton, 2014).



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CDR-MIP GMDD manuscript tables

Table 1. Overview of CDR-MIP experiments. In the "Forcing methods" column, "All" means "all anthropogenic, solar, and volcanic forcing". Anthropogenic forcing includes aerosol emissions, non-CO₂ greenhouse gas emissions, and land use changes.

Short Name	Long Name	Tier	Experiment Description	Forcing methods	Major purpose
<i>C1</i>	Climate and carbon cycle reversibility experiment	1	CO ₂ prescribed to increase at 1% yr ⁻¹ to 4x pre-industrial CO ₂ and then decrease at 1% yr ⁻¹ until again at a pre-industrial level, after which the simulation continues for as long as possible	CO ₂ concentration prescribed	Evaluate climate reversibility
<i>C2_pi-pulse</i>	Instantaneous CO ₂ removal / addition from an unperturbed climate experiment	1	100 Gt C is instantly removed (negative pulse) from a steady-state pre-industrial atmosphere; 100 Gt C is instantly added (positive pulse) to a steady-state pre-industrial atmosphere	CO ₂ concentration calculated (i.e., freely evolving)	Evaluate climate and C-cycle response of an unperturbed system to atmospheric CO ₂ removal; comparison with the positive pulse response
<i>C2_yr2010-pulse</i>	Instantaneous CO ₂ removal / addition from a perturbed climate experiment	2	100 Gt C is instantly removed (negative pulse) from a near present-day atmosphere; 100 Gt C is instantly added (positive pulse) to a near present-day atmosphere	All; CO ₂ concentration calculated (i.e., emission driven)*	Evaluate climate and C-cycle response of a perturbed system to atmospheric CO ₂ removal; comparison with the positive pulse response
<i>C2_overshoot</i>	Emission driven SSP5-3.4-OS scenario experiment	1	SSP5-3.4-overshoot scenario where CO ₂ emissions are initially high and then rapidly reduced, becoming negative	All; CO ₂ concentration calculated (i.e., emission driven)	Evaluate the Earth system response to CDR in an overshoot climate change scenario
<i>C3</i>	Afforestation/ reforestation experiment	1	Long-term extension of an experiment with forcing from a high CO ₂ emission scenario (SSP5-8.5), but with land use prescribed from a scenario with high levels of afforestation and reforestation (SSP1-2.6)	All; CO ₂ concentration calculated (i.e., emission driven)	Evaluate the long-term Earth system response to afforestation/ reforestation during a high CO ₂ emission climate change scenario
<i>C4</i>	Ocean alkalization experiment	1	A high CO ₂ emission scenario (SSP5-8.5) with 0.14 Pmol yr ⁻¹ alkalinity added to ice-free ocean surface waters from the year 2020 onward	All; CO ₂ concentration calculated (i.e., emission driven)	Evaluate the Earth system response to ocean alkalization during a high CO ₂ emission climate change scenario

*In this experiment CO₂ is first prescribed to diagnose emissions, however, the key simulations calculate the CO₂ concentration.



Table 2. Climate and carbon cycle reversibility experiment (*C1*) simulations. All simulations are required to complete the experiment.

Simulation ID	Simulation description	Owning MIP	Run length (years)
<i>piControl</i>	Pre-industrial prescribed CO ₂ control simulation	CMIP6 DECK	100*
<i>1pctCO2</i>	Prescribed 1% yr ⁻¹ CO ₂ increase to 4× the pre-industrial level	CMIP6 DECK	140**
<i>1pctCO2-cdr</i>	1% yr ⁻¹ CO ₂ decrease from 4× the pre-industrial level until the pre-industrial CO ₂ level is reached and held for as long as possible	CDR-MIP	200 min. 5000 max.

*This CMIP6 DECK should have been run for at least 500 years. Only the last 100 years are needed as a control for C1.

**This CMIP6 DECK experiment is 150 years long. A restart for C1 should be generated after 139 years when CO₂ is 4 times that of *piControl*.

Table 3. Instantaneous CO₂ removal from an unperturbed climate experiment (*C2_pi-pulse*) simulations.

Simulation ID	Simulation description	Owning MIP	Run length (years)
<i>esm-piControl</i>	Pre-industrial freely evolving CO ₂ control simulation	CMIP6 DECK	100*
<i>esm-pi-cdr-pulse</i>	100 Gt C is instantly removed (negative pulse) from a pre-industrial atmosphere	CDR-MIP	100 min. 5000 max.
<i>esm-pi-co2pulse</i>	100 Gt C is instantly added to (positive pulse) a pre-industrial atmosphere	CDR-MIP	100 min. 5000 max.

*This CMIP6 DECK should have been run for at least 500 years. Only the last 100 years are needed as a control for C2.1.



Table 4. Instantaneous CO₂ removal from a perturbed climate experiment (C2_yr2010-pulse) simulations.

Simulation ID	Simulation description	Owning MIP	Run length (years)
<i>historical</i>	Historical atmospheric CO ₂ (and other forcing) is prescribed until a concentration of 389ppm CO ₂ is reached	CMIP6 DECK	160*
<i>yr2010co2</i>	Branching from <i>historical</i> , atmospheric CO ₂ is held constant (prescribed) at 389ppm; other forcing is also held constant at the 2010 level	CDR-MIP	105 min. 5000 max.
<i>esm-hist-yr2010co2-control</i>	Control run forced using CO ₂ emissions diagnosed from <i>historical</i> and <i>yr2010co2</i> simulations; other forcing as in <i>historical</i> until 2010 after which it is constant	CDR-MIP	265 min. 5160 max.
<i>esm-yr2010co2-noemit</i>	Control run that branches from <i>esm-hist-yr2010co2-control</i> in year 2010 with CO ₂ emissions set to zero 5 years after the start of the simulation	CDR-MIP	105 min. 5000 max.
<i>esm-yr2010co2-cdr-pulse</i>	Branches from <i>esm-hist-yr2010co2-control</i> in year 2010 with 100 Gt C instantly removed (negative pulse) from the atmosphere 5 years after the start of the simulation	CDR-MIP	105 min. 5000 max.
<i>esm-yr2010co2-co2pulse</i>	Branches from <i>esm-hist-yr2010co2-control</i> in year 2010 with 100 Gt C instantly added to (positive pulse) the atmosphere 5 years after the start of the simulation	CDR-MIP	105 min. 5000 max.

*This CMIP6 DECK continues until the year 2150 but only the first 160 years are need for C2_yr2010-pulse.



Table 5. Emission driven SSP5-3.5-OS scenario experiment (*C2_overshoot*) simulations. All simulations are required to complete the experiment.

Simulation ID	Simulation description	Owning MIP	Run length (years)
<i>esm-hist</i>	Historical simulation forced with CO ₂ emissions	CMIP6 DECK	265
<i>esm-ssp534-over</i>	CO ₂ emission-driven SSP5-3.4 overshoot scenario simulation	CDR-MIP	85
<i>esm-ssp534-over-ext</i>	Long-term extension of the CO ₂ emission-driven SSP5-3.4 overshoot scenario	CDR-MIP	200 min. 5000 max.

Table 6. Afforestation/ reforestation experiment (*C3*) simulations. All simulations are required to complete the experiment.

Simulation ID	Simulation description	Owning MIP	Run length (years)
<i>esm-ssp585</i>	CO ₂ emission driven SSP5-8.5 scenario	C4MIP	85
<i>esm-ssp585-ssp126Lu</i>	CO ₂ emission driven SSP5-8.5 scenario with SSP1-2.6 land use forcing	LUMIP	85
<i>esm-ssp585-ssp126Lu-ext</i>	CO ₂ emission-driven SSP5-3.4 overshoot scenario simulation	CDR-MIP	200 min. 5000 max.
<i>esm-ssp585ext</i>	Long-term extension of the CO ₂ emission-driven SSP5-8.5 scenario	CDR-MIP	200 min. 5000 max.



Table 7. Ocean alkalization (C4) experiment simulations. "Pr" in the Tier column indicates a prerequisite experiment.

Simulation ID	Tier	Simulation description	Owning MIP	Run length (years)
<i>esm-ssp585</i>	Pr	CO ₂ emission driven SSP5-8.5 scenario	C4MIP	85
<i>esm-ssp585-ocean-alk</i>	1	SSP5-8.5 scenario with 0.14 Pmol yr ⁻¹ alkalinity added to ice-free ocean surface waters from the year 2020 onward	CDR-MIP	65
<i>esm-ssp585-ocean-alk-stop</i>	3	Termination simulation to investigate an abrupt stop in ocean alkalization in the year 2070	CDR-MIP	30*
<i>esm-ssp585ext</i>	2	Long-term extension of the CO ₂ emission-driven SSP5-8.5 scenario	CDR-MIP	200 min. 5000 max.
<i>esm-ssp585-ocean-alk-ext</i>	2	Long-term extension of the <i>esm-ssp585-ocean-alk</i> simulation	CDR-MIP	200 min. 5000 max.

*If the *esm-ssp585ext* simulation is being conducted this may be extended for more than 200 more years (up to 5000 years).



Table 8. Model output frequency for 3-D models with seasonality. Box models and EMICs without seasonality are expected to generate annual global mean output for the duration of all experiments. For longer simulations (right column) if possible 3-D monthly data should be written out for one year every 100 years. For models with interannual variability, e.g., ESMs, monthly data should be written out for a 10-year period every 100 years so that a climatology may be developed. The years referred to in the table indicate simulations years, e.g. years from the start of the run, not that of any particular scenario.

Experiment Short Name	Individual simulation output frequency	
	Monthly gridded 3-D output	Annual global mean output + climatological output at 100 year intervals
<i>C1</i>	<i>piControl</i> (last 100 years) <i>1pctCO2</i> <i>1pctCO2-cdr</i> (initial 200 years)	<i>1pctCO2-cdr</i> (from year 200 onward)
<i>C2_pi-pulse</i>	<i>esm-piControl</i> <i>esm-pi-cdr-pulse</i> (initial 100 years) <i>esm-pi-co2pulse</i> (initial 100 years)	<i>esm-pi-cdr-pulse</i> (from year 100 onward) <i>esm-pi-co2pulse</i> (from year 100 onward)
<i>C2_yr2010-pulse</i>	<i>esm-hist-yr2010co2-control</i> (initial 105 years) <i>esm-yr2010co2-noemit</i> <i>esm-yr2010co2-cdr-pulse</i> <i>esm-yr2010co2-co2pulse</i>	<i>esm-hist-yr2010co2-control</i> <i>esm-yr2010co2-noemit</i> <i>esm-yr2010co2-cdr-pulse</i> <i>esm-yr2010co2-co2pulse</i>
<i>C2_overshoot</i>	<i>esm-hist</i> <i>esm-ssp534-over</i> <i>esm-ssp534-over-ext</i> (initial 200 years)	<i>esm-ssp534-over-ext</i> (from year 200 onward)**
<i>C3</i>	<i>esm-ssp585ext</i> (initial 200 years) <i>esm-ssp585-ssp126Lu</i> <i>esm-ssp585-ssp126Lu-ext</i> (initial 200 years)	<i>esm-ssp585ext</i> (from year 200 onward)** <i>esm-ssp585-ssp126Lu-ext</i> (from year 200 onward)**
<i>C4</i>	<i>esm-ssp585</i> <i>esm-ssp585-ocean-alk</i> <i>esm-ssp585-ocean-alk-stop</i> (initial 200 years) <i>esm-ssp585ext</i> (initial 200 years) <i>esm-ssp585-ocean-alk-ext</i> (initial 200 years)	<i>esm-ssp585-ocean-alk-stop</i> (from year 200 onward)** <i>esm-ssp585ext</i> (from year 200 onward)** <i>esm-ssp585-ocean-alk-ext</i> (from year 200 onward)**

*In the *historical* and *yr2010co2* simulations output is needed only to diagnose (at least annually) CO₂ emissions.

**This is from scenario year 2300 onward.

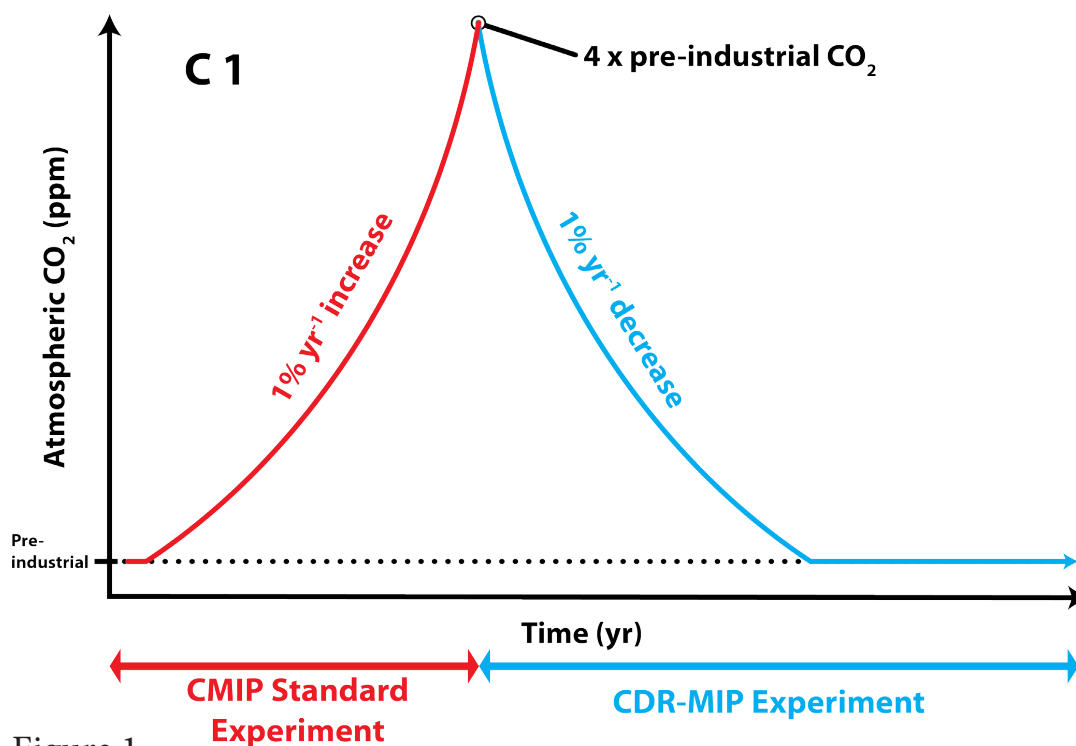


Figure 1

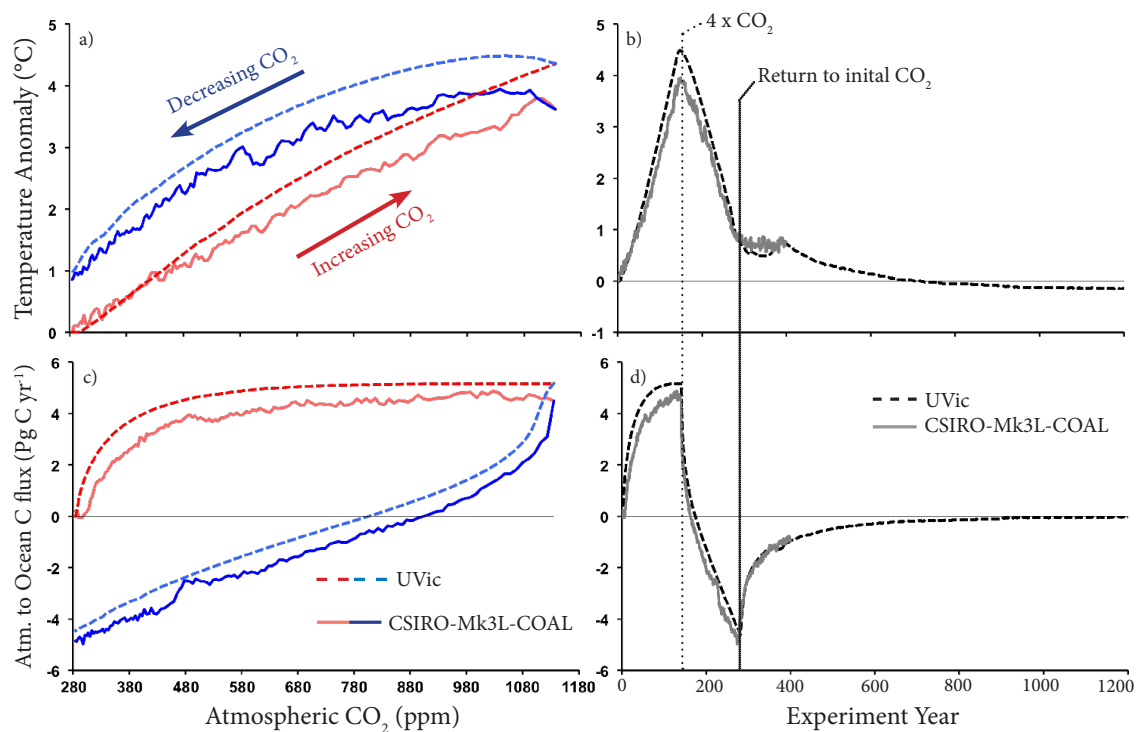


Figure 2

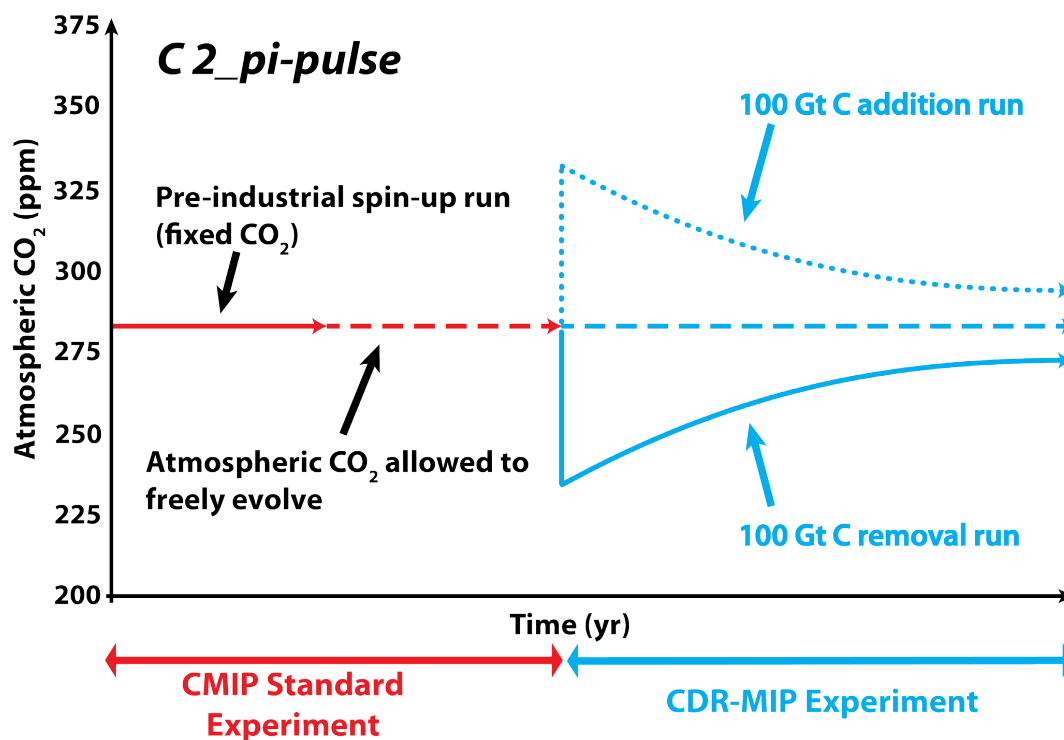


Figure 3

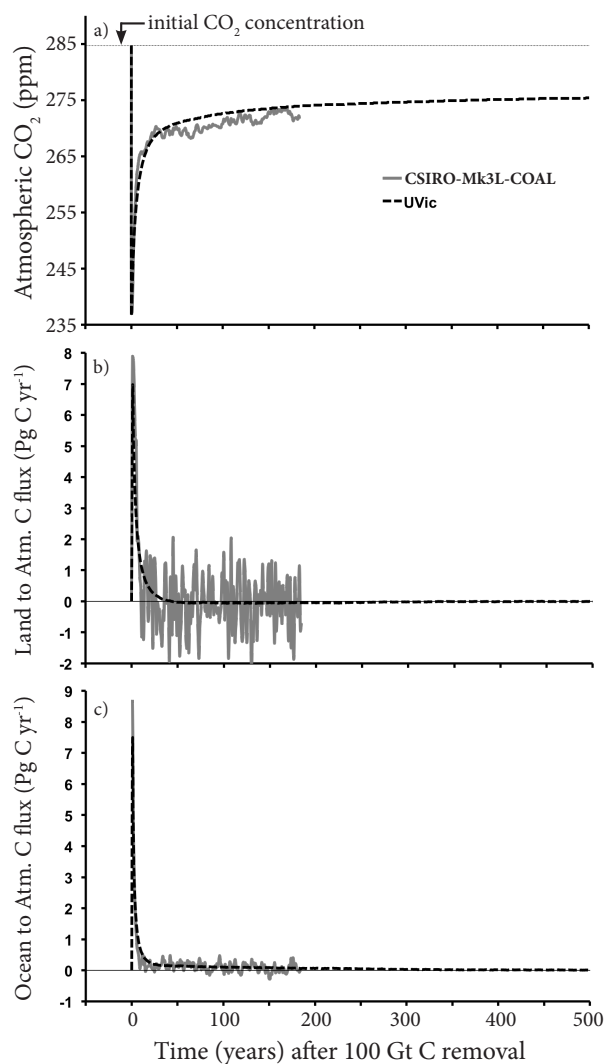


Figure 4

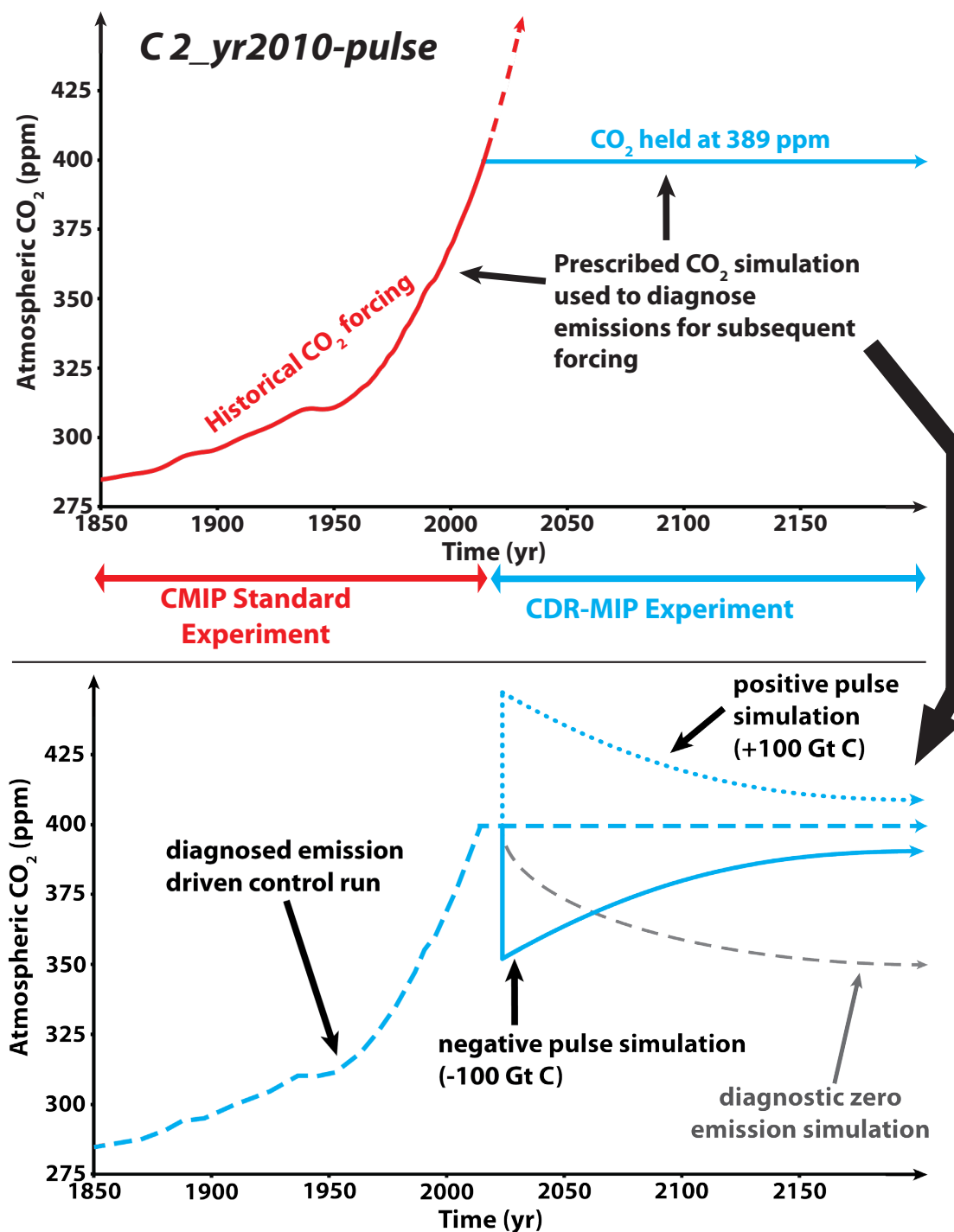


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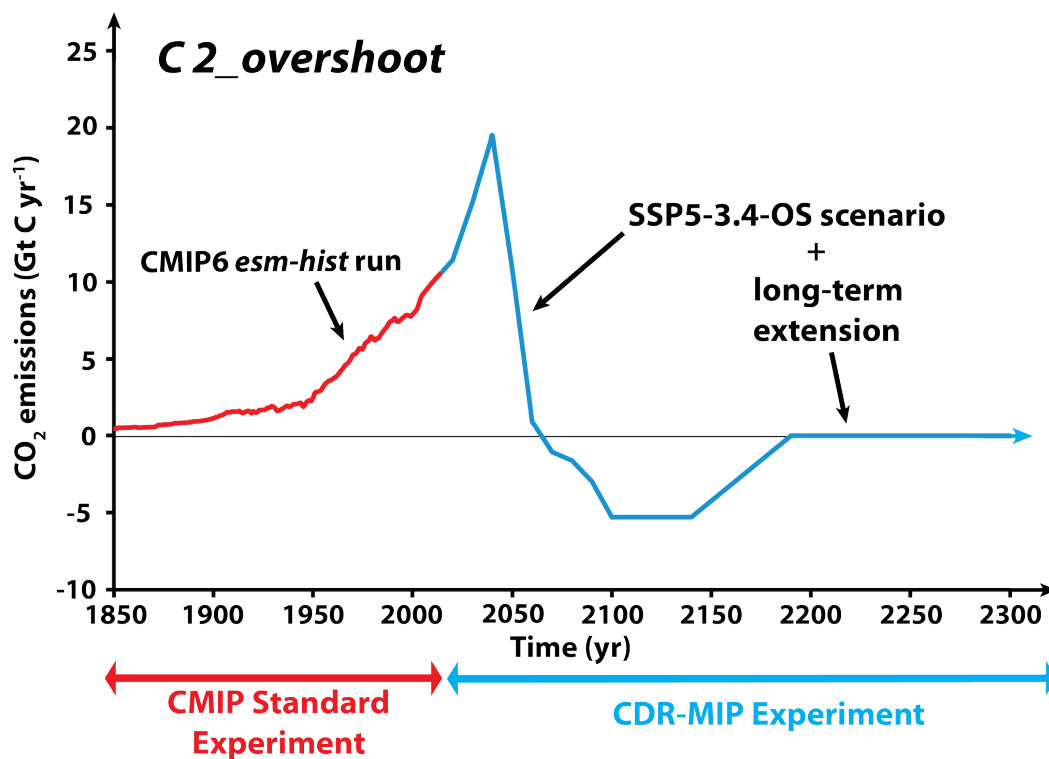


Figure 6



1 Figure 1. Schematic of the CDR-MIP climate and carbon cycle reversibility
2 experimental protocol (*C1*). From a preindustrial run at steady state atmospheric
3 CO₂ is prescribed to increase and then decrease over a ~280 year period, after
4 which it is held constant for as long as computationally possible.

5
6 Figure 2. Exemplary climate and carbon cycle reversibility experiment (*C1*)
7 results with the CSIRO-Mk3L-COAL Earth system model and the University of
8 Victoria (UVic) Earth system model of intermediate complexity (models are
9 described in Appendix D). The left panels show annual global mean (a)
10 temperature anomalies (°C; relative to pre-industrial temperatures) and (c) the
11 atmosphere to ocean carbon fluxes (Pg C yr⁻¹) versus the atmospheric CO₂ (ppm)
12 during the first 280 years of the experiment (i.e., when CO₂ is increasing and
13 decreasing). The right panels show the same (b) temperature anomalies and (d)
14 the atmosphere to ocean carbon fluxes versus time. Note that the CSIRO-Mk3L-
15 COAL simulation was only 400 years long.

16
17 Figure 3. Schematic of the CDR-MIP instantaneous CO₂ removal / addition from
18 an unperturbed climate experimental protocol (*C2_{pi}-pulse*). Models are spun-up
19 for as long as possible with a prescribed preindustrial atmospheric CO₂
20 concentration. Then atmospheric CO₂ is allowed to freely evolve for at least 100
21 years as a control run. The negative / positive pulse experiments are conducted
22 by instantly removing or adding 100 Gt C to the atmosphere of a simulation
23 where the atmosphere is at steady state and CO₂ can freely evolve. These runs
24 continue for as long as computationally possible.

25
26 Figure 4. Exemplary instantaneous CO₂ removal from a preindustrial climate
27 experiment (*C2_{pi}-pulse*) results from the *esm-pi-cdr-pulse* simulation with the
28 CSIRO-Mk3L-COAL Earth system model and the University of Victoria (UVic)
29 Earth system model of intermediate complexity (models are described in
30 Appendix D). (a) shows atmospheric CO₂ vs. time, (b) the land to atmosphere
31 carbon flux vs. time, and (c) the ocean to atmosphere carbon flux vs. time. Note
32 that the Mk3L-COAL simulation was only 184 years long.

33



34 Figure 5. Schematic of the CDR-MIP instantaneous CO₂ removal / addition from a
35 perturbed climate experimental protocol (*C2_{yr2010-pulse}*). Top panel: Initially
36 historical CO₂ forcing is prescribed and then held constant at 389 ppm (~ year
37 2010) while CO₂ emissions are diagnosed. Bottom panel: A control simulation is
38 conducted using the diagnosed emissions. The negative / positive pulse
39 experiments are conducted by instantly removing or adding 100 Gt C to the
40 atmosphere of the CO₂ emission-driven simulation 5 years after CO₂ reaches 389
41 ppm. Another control simulation is also conducted that sets emissions to zero at
42 the time of the negative pulse. The emission-driven simulations continue for as
43 long as computationally possible.

44

45

46 Figure 6. Schematic of the CDR-MIP emission-driven SSP5-3.4-OS scenario
47 experimental protocol (*C2_{overshoot}*). A CO₂ emission-driven historical
48 simulation is conducted until the year 2015. Then an emission-driven simulation
49 with SSP5-3.4-OS scenario forcing is conducted. This simulation is extended until
50 the year 2300 using SSP5-3.4-OS scenario long-term extension forcing.
51 Thereafter, runs may continue for as long as computationally possible with
52 constant forcing after the year 2300.